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EVALUATION OF IRRIGATION SCHEDULING FOR SALINITY CONTROL IN GRAND VALLEY

Gaylord Skogerboe, et al

Colorado State University

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EVALUATION OF IRRIGATION SCHEDULING FOR SALINITY CONTROL IN GRAND VALLEY

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ABSTRACT

Irrigation return flows carrying large salt loads as a result of contact with saline soils and aquifers have caused serious salinity problems in the Colorado River Basin. The Grand Valley in western Colorado is a major contributor to the salinity problems in the basin and is therefore a logical region to test the effectiveness of salinity control alternatives. This study has emphasized two on-farm measures; namely, irrigation scheduling and tile drainage.

Two small farms were extensively investigated during the two-year interval of the project to identify the structural and non-structural requirements for maximizing water use efficiencies. Early season irrigations are shown to provide significantly more salts in the river system than later ones. Irrigation scheduling programs are shown to be effective only when sufficient structural rehabilitation and labor input are implemented to allow complete adherence to the scheduling suggestions. Because of the relatively inflexible method of irrigation in Grand Valley, irrigation scheduling must be implemented as a segment of a valley-wide salinity control program.

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SECTION I

CONCLUSIONS

The irrigation of agricultural lands in the Colorado River Basin is a significant cause of the salinity concentrations encountered in the Colorado River. Emphasis towards stemming further salinity increases has logically centered upon improving the quality of irrigation return flows. This emphasis, especially in the high salt contributing areas like the Grand Valley in western Colorado, focuses upon reducing the flows which pass through the saline soils and aquifers, thereby reducing the salt pickup that occurs by dissolution. Since a major fraction of the water contacting local soils in this manner comes from over-irrigation, measures aimed at improving irrigation efficiencies promise good potential for controlling salinity. Among the methods for achieving higher water use efficiencies on the farm, "scientific" irrigation scheduling is possibly the most important.

Irrigation scheduling consists of two primary components; namely, evapotranspiration and available root zone soil moisture. Evapotranspiration is calculated by using climatic data. The other major category of required data pertains to soil characteristics. First of all, field capacity and wilting point for the particular soils in any field must be determined. More importantly, infiltration characteristics of the soils must be measured. Only by knowing how soil intake rates change with time during a single irrigation, as well as throughout the irrigation season, can meaningful predictions be made as to: (a) the quantity of water that should be delivered at the farm inlet for each irrigation; and (b) the effect of modifying deep percolation losses. With good climatic data and meaningful soils data, accurate predictions as to the next irrigation date and the quantity of irrigation water to be applied can be made. In order to insure that the proper quantity of water is applied, a flow measurement structure is absolutely required at the farm inlet.

The results of this demonstration project indicate that irrigation scheduling programs have a limited effectiveness for controlling salinity in the Grand Valley under existing conditions. Excessive water supplies, the necessity for rehabilitating the irrigation system (particularly the laterals), and local resistance to change preclude managing the amounts of water applied during successive irrigations. To overcome these limitations, irrigation scheduling must be accompanied by flow measurement at all the major division

points, farm inlets, and field tailwater exits. In addition, it is necessary for canal companies and irrigation districts to assume an expanded role in delivery of the water. Also, some problems have been encountered involving poor communication between farmer and scheduler, as well as certain deficiencies in the scheduling program dealing with evapotranspiration and soil moisture predictions. These latter problems can be easily rectified, however. Correcting these conditions will make irrigation scheduling much more effective and acceptable locally.

Water budgets from which the study results were generated resulted from intensive investigation on two local farms. The selection of the two study farms was intended to be representative of conditions valley-wide. Analysis of the budgets reveal that approximately 50% of the water applied to the fields came during the April and May period when less than 20% of the field evapotranspiration potential had been experienced. Salt pickup estimates during this early part of the season amounted to about 60% of the annual total for each field. Another indication of the importance of early season water management is presented in an analysis of irrigation efficiencies. As the season progressed, the soils became less permeable and the crop water use increased, causing marked improvements in irrigation efficiency. Thus, if irrigation scheduling is employed in its optimal format, salt pickup from the two fields could have been reduced as much as 50% or more.

The results of this demonstration project show that irrigation scheduling is a necessary, but not sufficient, tool for achieving improved irrigation efficiencies. The real strides in reducing the salt pickup resulting from over-irrigation will come from the employment of scientific irrigation scheduling in conjunction with improved on-farm irrigation practices. This combined effect could result in reduction of 300,000 tons annually of salt pickup from the Grand Valley, depending upon the degree of improvement in present on-farm irrigation practices.

SECTION II

RECOMMENDATIONS

Although the results of this study indicate that existing programs for irrigation scheduling in the Grand Valley to control salinity are having only a marginal effect, the potential for "scientific" irrigation scheduling has been well established. The recommendations generated by experience on this project are basically two dimensional. The first regards the improvements necessary to achieve an effective scientific irrigation scheduling program and the second deals with future evaluations which could be undertaken to remedy mounting salinity problems in the Colorado River Basin.

Irrigation scheduling should not be taken individually as a salinity control measure because its effectiveness is not exclusive of the operations of the total irrigation system. It is utter foolishness to advise an irrigator to apply three inches of water when he does not have the capability of measuring the amount of water applied. Past experience and personal judgment are no substitutes for accurate measurement. Consequently, irrigation scheduling should not divorce itself from the improvement of flow measurement at both the canal turnout and the field inlet. Also, if tailwater runoff occurs (which is usually the case in Grand Valley) a flow measurement structure should be installed at each field outlet. In addition, when the soils are known to be affected by year-to-year practices and climatic conditions, the operation of the irrigation system, including suggestions for timing and application from the scheduling printout, should incorporate necessary changes for each condition.

The evaluation of conveyance channel linings completed in previous studies, along with the investigation of irrigation scheduling and field drainage in this effort, represent major steps towards a completely developed salinity control technology. This work and that being undertaken by researchers throughout the West can now begin to be integrated into regional salinity control strategies. Salinity control strategies represent the integration of individual control measures into a coordinated program. Such policies depend not only upon the effectiveness of each measure, but individual costs as well; suggesting that the next phase of salinity control investigation should develop and combine the cost-effectiveness for individual salinity control measures into strategies for achieving varying degrees of salinity control in the Grand Valley. For example, both the cost and the

expected salt pickup reduction should be established for various on-farm irrigation improvements such as flow measurement devices, increased labor for irrigation, automated farm head ditches, gated pipe, cut-back furrow irrigation, sprinkler irrigation, trickle irrigation, etc.

SECTION III

INTRODUCTION

STATEMENT OF THE PROBLEM

In April of 1972, the seven basin states sharing the water resources of the Colorado River Basin (Fig. 1) and the U. S. Environmental Protection Agency (EPA) responsible for the quality of such flows agreed to the necessity of maintaining the concentrations of salts in the lower basin at or below existing levels (U. S. Environmental Protection Agency, 1972). Further, the necessity to allow Upper Basin users to proceed with the development of waters apportioned to them under the Colorado River Compact of 1922 was realized. These two segments of the statements emanating from the enforcement conference are, however, contradictory without accompanying each new development with sufficient reductions in existing salt loads to compensate for the effects of the new water use.

The collective decisions regarding the control of salinity in the basin have been induced by the mounting damages incurred by downstream users. Salinity problems are also of international concern owing to the detriments being experienced in the Mexicali Valley of the Republic of Mexico. The methods available for controlling salinity include phreatophyte eradication, reducing evaporation, desalination, elimination of mineralized point sources, importing supplemental water, and improving agricultural, municipal, and industrial water use practices. While certain of these alternatives may be either technologically impractical or politically unacceptable, they represent the array of alternatives from which an overall strategy must be generated. Because of the limited effectiveness of each measure, such a strategy for salinity control must be a combination of several feasible alternatives. The first task is, therefore, to develop the costs and the effectiveness of the individual salinity control measures.

One examination of the sources of salinity in the basin, shown in Fig. 2, reveals that of the man-made contributions, irrigated agriculture has the largest effect. Consequently, the major aspect of salinity control in the region must be the effective use of irrigation diversions by improving the efficiency of conveyance, farm, and wastewater systems. One of the several important efforts funded by the U. S. Environmental Protection Agency to develop salinity control technology is the Grand Valley Salinity Control Demonstration Project in western Colorado (Fig. 3). This report describes

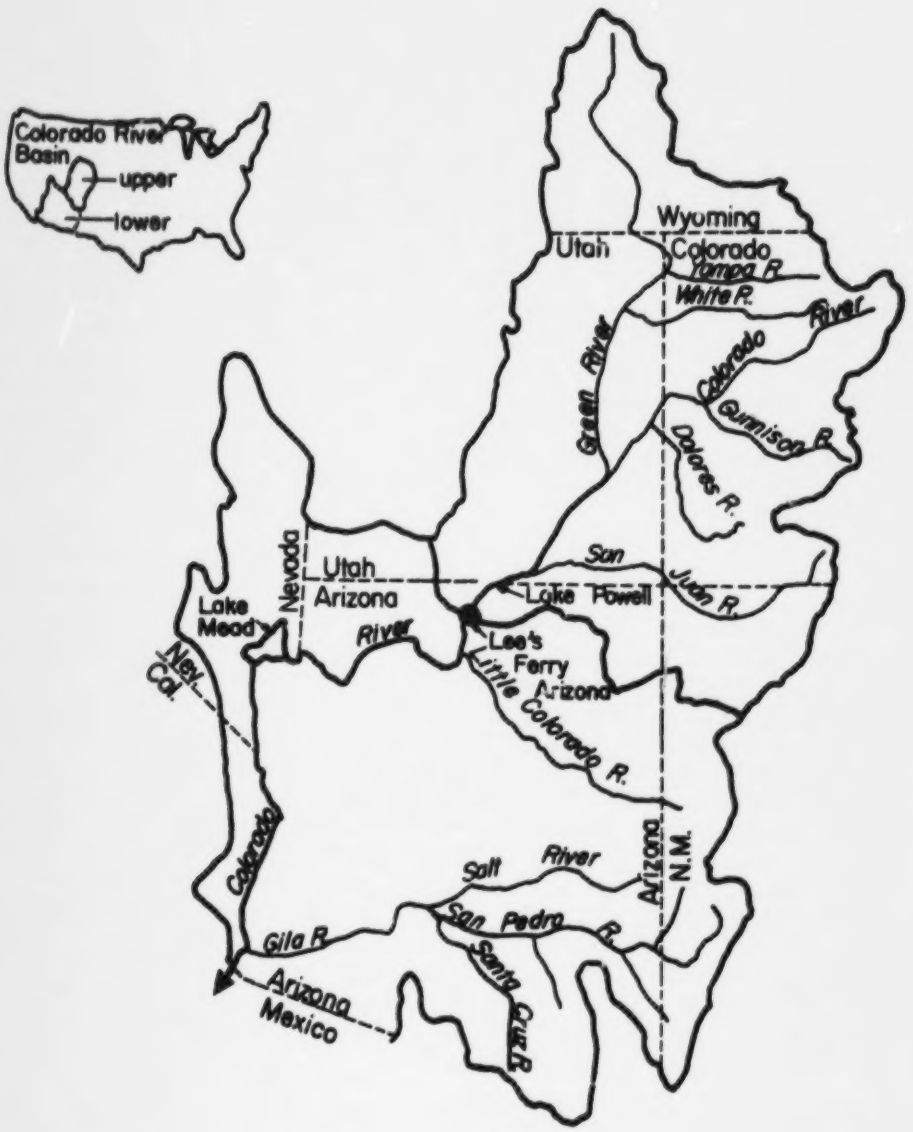
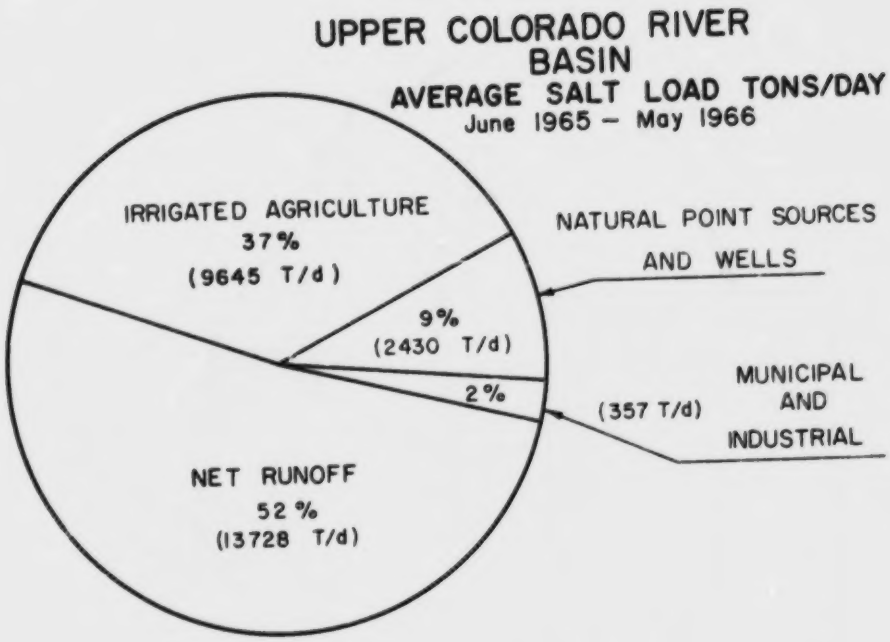


Fig. 1. The Colorado River Basin.



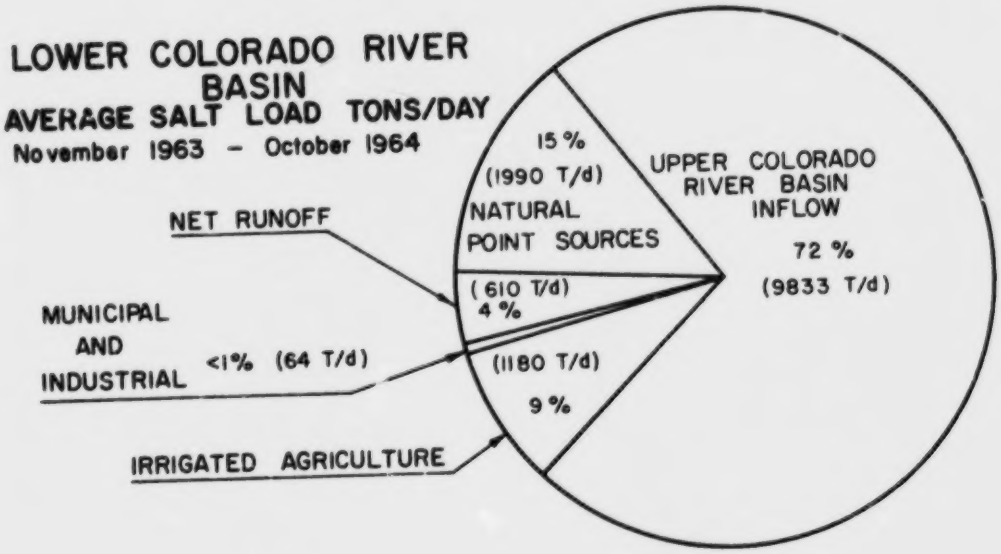


Fig. 2. Major sources of salinity in the Colorado River Basin.

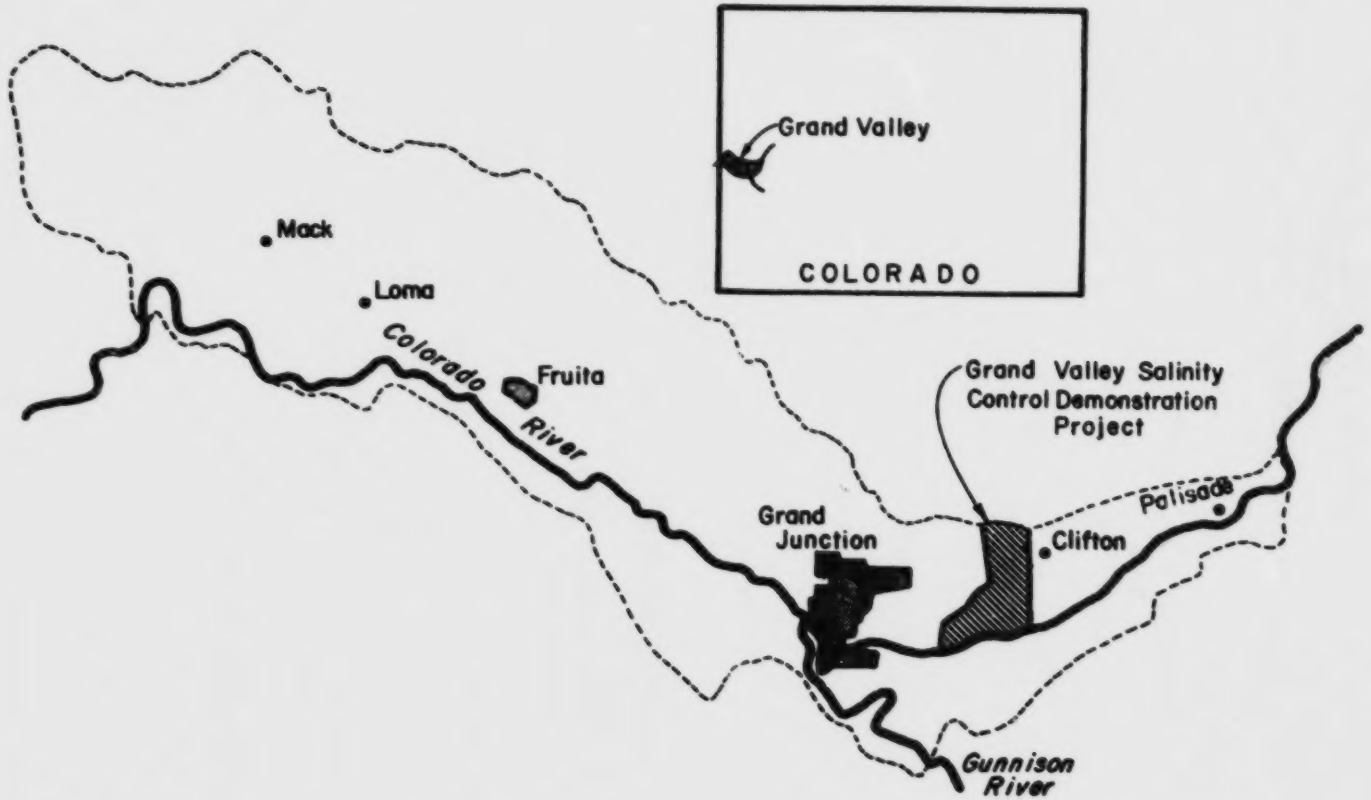


Fig. 3. The Grand Valley of Colorado.

the project's role in testing irrigation scheduling as a salinity control measure. Although irrigation scheduling is a two-dimensional technique involving both the timing of an irrigation and control of the quantities of water entering the root zone, many of the applications to date have emphasized primarily the timing aspects. As the nation has realized the necessity for improving water use practices to stretch existing supplies and minimize water quality degradation, the focus of irrigation scheduling is beginning to achieve its full scope—the inter-relationship between improved water management and improved water quality of irrigation return flows.

THE STUDY AREA

The Grand Valley area is one of the most significant salinity inputs to the Colorado River system, and therefore, is a logical area to develop salinity control technology. Water entering the near-surface aquifers in the valley become heavily laden with salts dissolved from the soils and aquifers of marine origin which occur extensively in the area. The primary source of these soils and aquifers is the Mancos Shale formation which was formed as a result of the alternate advance and recession of the great inland seas once dominating the western United States. Since the water entering local aquifers comes mainly from irrigation channel seepage and deep percolation from excessive and inefficient irrigations, the emphasis of a salinity control technology is to maximize the efficiencies of both the conveyance and farm water use subsystems.

Agricultural Land Use

Although the early explorers concluded that the Grand Valley was a poor risk for agriculturally related activities, the first pioneering farmers rapidly disproved this notion with the aid of irrigation water diverted from the rivers (Colorado and Gunnison) entering the valley. Through a long struggle, an irrigation system evolved to supplement the otherwise meager supply of precipitation (Fig. 4) during the hot summer months. However, the futility of irrigation without adequate drainage was quickly demonstrated in the valley as low lying acreage became waterlogged with highly saline groundwater. Today, the failure to completely overcome these conditions is still evident as illustrated by a summary of land use in the valley presented in Fig. 5. For example, of the more than 70,000 acres of irrigable cropland, almost one-third is either in pasture or idle. An examination of land use in Grand Valley by Walker and Skogerboe (1971) indicates

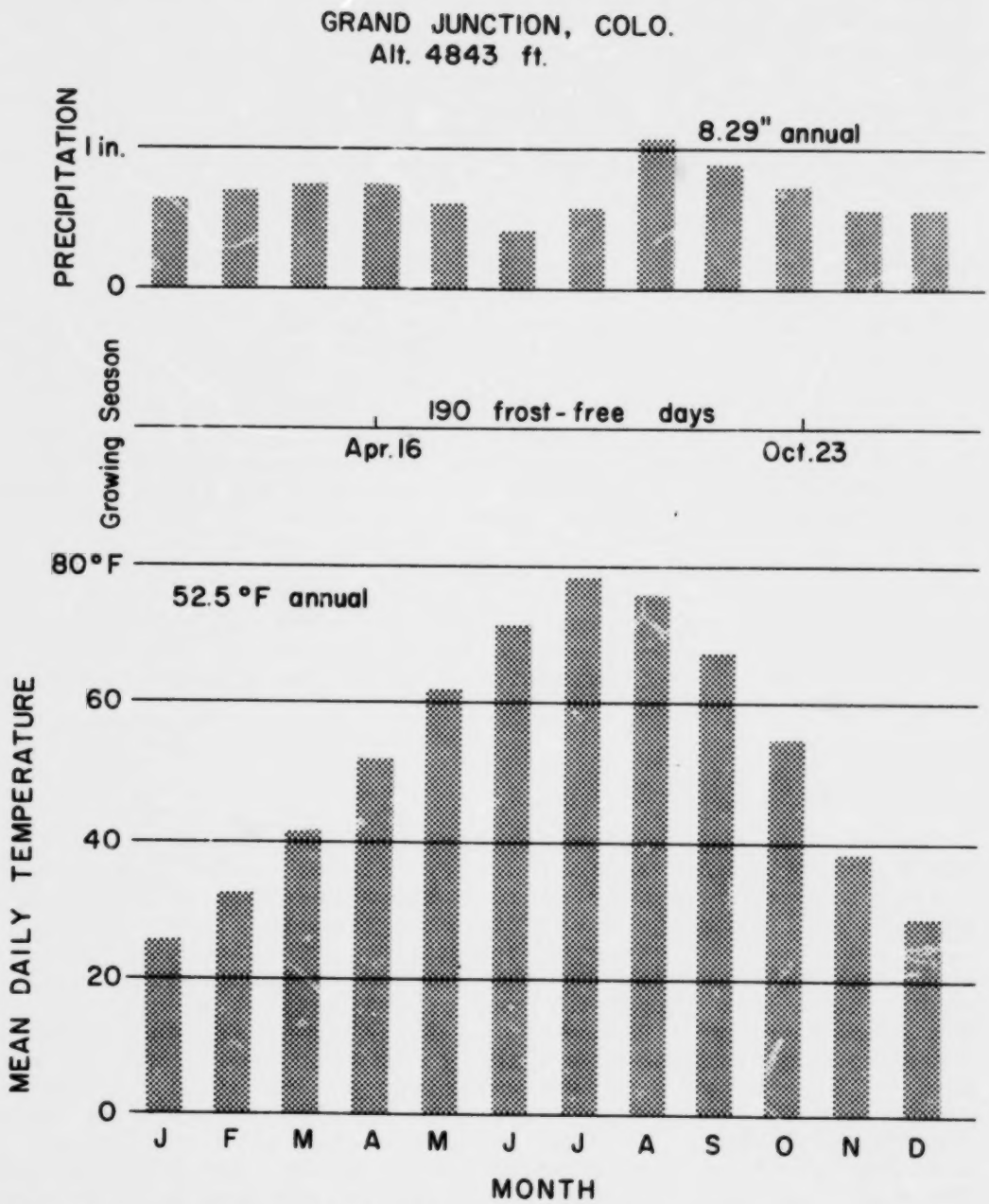


Fig. 4. Normal precipitation and temperature at Grand Junction, Colorado.

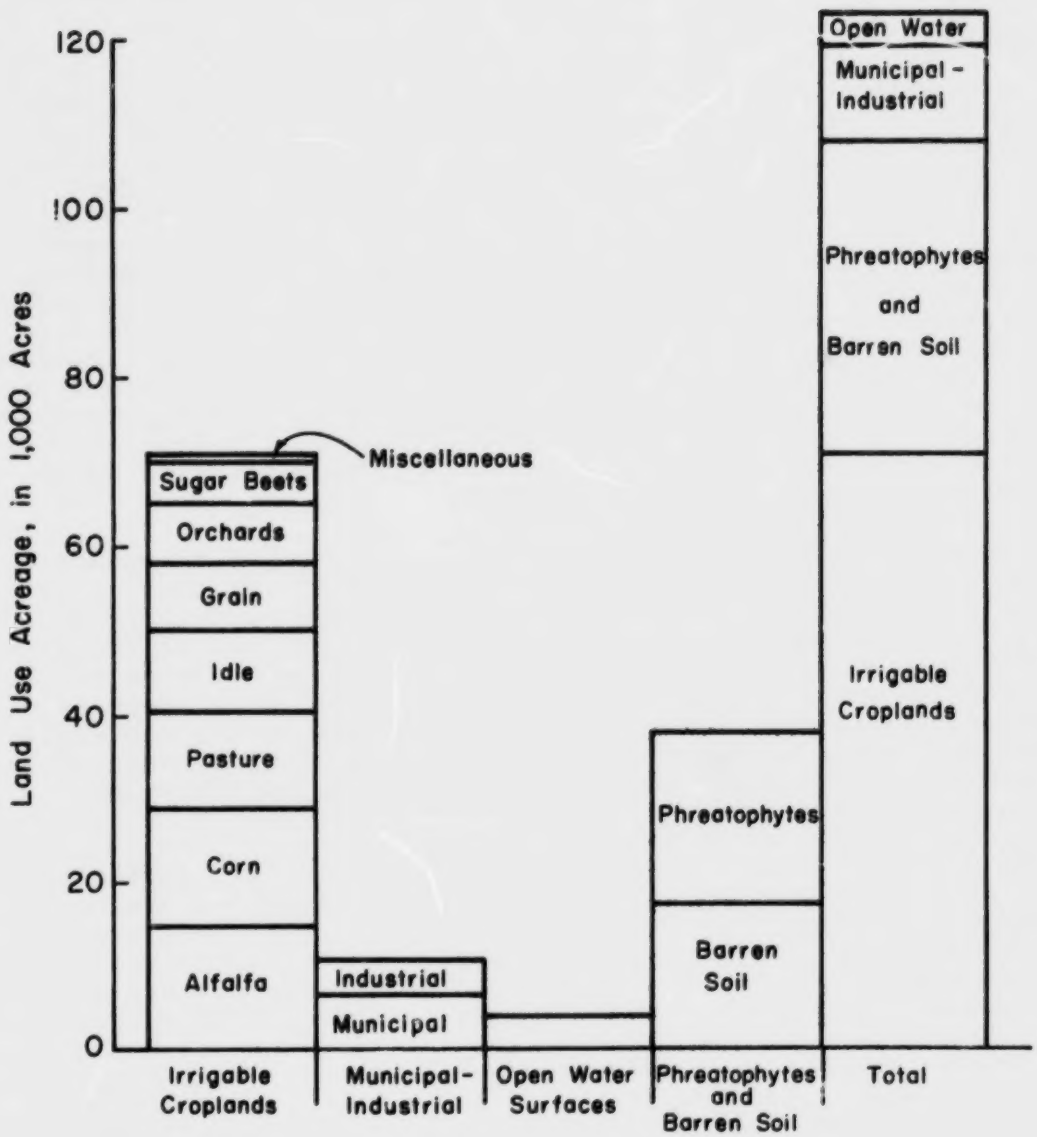


Fig. 5. Agricultural land use in the Grand Valley.

a fraction of the 30-40 thousand acres of phreatophytes and barren soil were also once part of an irrigated acreage. Evidence exists that these same lands were once highly productive and subsequently ruined by over-irrigation and inadequate drainage.

Irrigation Practices

The prevalent method of applying water to croplands in the valley is furrow irrigation. Small laterals carrying one to five cubic feet per second (cfs) divert water from the company or district operated canal systems to one or more irrigators. Water then flows into field head ditches where it is applied to the lands to supply the growing crops and maintain a salt-free root zone environment. The predominant alfalfa, corn, sugar beet, orchard, and small grain economy is served by a more than adequate water supply. The 70,830 acres of irrigable cropland encompassed within the irrigation system enjoys a total diversion of more than eight acre-feet per acre during normal years. Considering that the potential evapotranspiration of these croplands is usually less than three acre-feet per acre, it is obvious that existing water use efficiencies are low.

Enough variation in climate exists in the valley to separate the agricultural land use into three primary regions. In the eastern end of the valley, the protective proximity to the abrupt Grand Mesa results in extended periods of frost-free days which allows apple, peach, and pear orchards to abound. In the western half of the valley, the primary emphasis is on producing corn, alfalfa, sugar beets, and small grains. Between these two regions is a transition zone of small farms and the urban setting of Grand Junction—the population center of the area.

The farms in this transition area are particularly affected by adverse conditions, and high salt contributions are being returned to the Colorado River. The intensive study area for the Grand Valley Salinity Control Demonstration Project, illustrated in Fig. 3, was selected here. The primary advantage for undertaking the studies in this area was that earlier phases of the Grand Valley Salinity Control Demonstration Project were conducted here and thus a great deal of data was already available to facilitate this investigation. Also, accomplishments achieved under adverse conditions are much more meaningful than improvements on the better agricultural lands.

PURPOSE OF STUDY

The central purpose of this project has been to further the development of technology needed to improve the quality of flows returning to the Colorado River. Because the agricultural water uses have been the largest contributors to the conditions which now exist, the emphasis has been primarily directed at improving both structural and non-structural components to minimize the groundwater flows contacting the saline subsurface geologic formations. The initial phase was begun in 1968 to evaluate canal and lateral linings as salinity control measures. Those results, reported by Skogerboe and Walker (1972), demonstrated the need for further investigations concerning on-farm water management practices. As a result, a second and third phase program was undertaken to determine the feasibility of two farm management improvements—irrigation scheduling and drainage—in controlling salinity. This report is presented to summarize the findings related to irrigation scheduling as a salinity control measure.

SCOPE OF STUDY

The experience and data generated by the first phase of this project have been important prerequisites to the successful completion of this study. The scope of the field investigations, however, was changed to reflect the increased interest on the farm itself. This allowed a more intensive evaluation of irrigation practices with less emphasis on the area-wide hydro-salinity flow system because of previous knowledge gained from earlier studies.

Five fields in the demonstration area were incorporated into the study to represent a cross-section of agricultural practices in the Grand Valley. These farms, located in Fig. 6 and described in Table 1, were included in an irrigation scheduling service implemented in the valley by the local U. S. Bureau of Reclamation (USBR) office, thereby allowing the efforts of this investigation to be coordinated with the USBR irrigation scheduling program.

Since the test area is characteristically operated by small unit farmers and the soils are severely affected by the high water table conditions, agricultural productivity is not presently sufficient to support most of the occupants, and many have outside jobs in local businesses or industry. One of the concerns of the investigators was in demonstrating the value of the scheduling service to these individual land owners. In addition, these lands were once among the

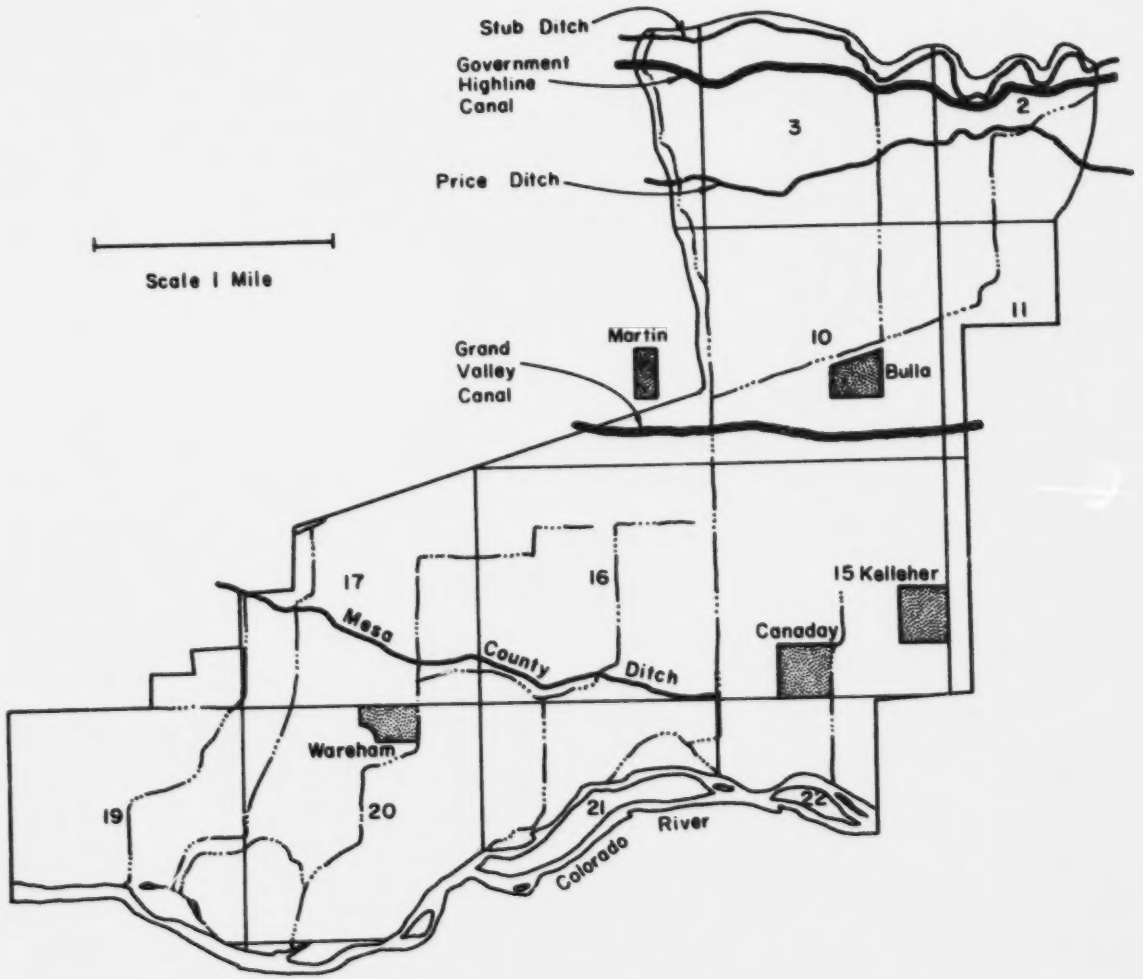


Fig. 6. Location of study farms in the demonstration area.

Table 1. Description of farms in the demonstration area included in the 1973 irrigation scheduling studies.

Farm	Crop	Crop Acreage	Field Capacity	Wilting Point, %
Martin	Corn	9.2	22.3	10.7
Bulla	Barley	10.7	24.2	13.4
	Corn	15.0	23.9	12.1
Canaday	Barley	17.1	26.5	12.8
Kelleher	Oats	9.8	25.0	12.2
	Pasture	1.0	25.8	14.1
Wareham	Alfalfa	17.4	30.5	16.7
	Crested Wheatgrass	13.6	29.3	16.7

valley's most productive (at the turn of the last century) and a significant impetus could be generated locally in support of salinity control programs if such measures were effective in returning these lands to a high level of agricultural productivity.

In this study, an effort has been made to evaluate irrigation scheduling under various management conditions ranging from little or no improvements in on-farm irrigation practices to maximum use of the scheduling recommendations. Three of the farms, namely the Kelleher, Canaday, and Wareham farms, were included primarily as part of the third phase of this project involving field drainage, but were included in the scheduling program to yield a linkage between the two studies. The two fields referred to as the Martin and Bulla farms were intensively studied to evaluate the potential for salinity control resulting from irrigation scheduling, along with the requirements for maximizing this potential in the Grand Valley with structural and non-structural improvements in the agricultural system.

In addition to the on-farm evaluations, the data collection and analysis of important hydro-salinity parameters in the study area were continued on a reduced level to provide continuity with earlier data. The investigators concluded that such efforts were necessary to detect any changes relative to the improvement of water management practices in the area, while providing a unique opportunity to refine the results of the earlier study, if desired. Of course, the size, scope, and detail with which any research and/or demonstration effort is conducted must be compromised with the time, talent, and funding provided to the researchers. A workable balance was achieved in this project while maintaining a high degree of sensitivity towards the goals of the project.

SECTION IV

SCIENTIFIC IRRIGATION SCHEDULING

HISTORICAL PERSPECTIVE

Since the days in the Tigris and Euphrates Valleys centuries ago, farmers engaged in irrigated agriculture have had to face the critical decisions of how and when to irrigate their lands. Consequently, irrigation scheduling in its most primitive form emerged long before the advent of digital computers, climatological monitors, or instantaneous communications systems. Present day investigations and applications of this long known concept have produced great strides towards broadening the scope of irrigation scheduling to meet the requirements of a modern agricultural technology. Important and new dimensions are necessities if modern agriculture is to effectively challenge such threatening problems as world food and fiber shortages, deteriorating environmental quality, and the increasing demands upon limited supplies of natural resources.

Until the development of the present irrigation scheduling technology, an irrigator was primarily dependent on the judgment and experiences of his immediate associates and himself. For example, the farmers who produced the most were often able to judge the need for an irrigation based on the appearance of the crops. In fact, this requirement remains as one of the most effective tools in the production of specialized crops (e.g., alfalfa seed) today. However, the fallibility of experience and judgment has been demonstrated throughout the world, as over-application of water has led to yield reductions due to fertilizer leaching, poor soil aeration, and plant diseases. In addition, such inefficient irrigation practices have created regional water quality problems, mosquito nuisances, public health problems, and local property damage due to waterlogging of soils and seepage of water into basements of homes and businesses.

The refinement in irrigation scheduling techniques has provided interested farmers with a tool for minimizing the deleterious effects of poor water management. By basing the scheduling service on a thorough understanding of the primary parameters affecting crop water demands, a consistent and reliable program can be implemented. The components of the current scheduling services were developed and evaluated in 1966 and 1967 in southern Idaho by personnel of the Agricultural Research Service, U. S. Department of Agriculture. Beginning in 1968 and 1969, the program found wide acceptance in Arizona, Nebraska, Kansas, Washington, and

California (Jensen, 1972). The objectives of the irrigation scheduling programs are five-fold (U. S. Department of the Interior, 1971):

1. Increase crop yields and quality;
2. Reduce fertilizer losses;
3. Reduce the amount of unnecessary water and labor inputs to farming;
4. Reduce drainage problems; and
5. Improve the quality of return flows.

The success in developing this scheduling program was assured by the years of study of crop water requirements and irrigation methods.

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Similar studies were started in Utah by Mills (1890) along with other studies initiated throughout the West on funds provided by the Appropriation Act of 1898. Most of the early studies involved the measurement of water delivered to irrigated farms.

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Studies by Briggs and Shantz (1913) were initiated near Akron, Colorado, in 1910-1913 involving up to 55 species and various plants. Since these studies were not conducted under field conditions, the authors stated that "the water requirement measurements must therefore be considered relative rather than absolute." This basic data qualification was often overlooked or disregarded for the next half-century. In recording meteorological data, Briggs and Shantz also recognized that solar radiation was the primary cause of the cyclic changes of environmental factors and that sensible heat from the air contributed materially to energy dissipated by transpiration.

California (Jensen, 1972). The objectives of the irrigation scheduling programs are five-fold (U. S. Department of the Interior, 1971):

1. Increase crop yields and quality;
2. Reduce fertilizer losses;
3. Reduce the amount of unnecessary water and labor inputs to farming;
4. Reduce drainage problems; and
5. Improve the quality of return flows.

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During the next two decades more emphasis was placed on methods of estimating seasonal consumptive use. Problems of nonrepresentative environmental conditions around pots or containers, and unsaturated drainage between sampling dates were recognized. The energy balance concept, which was applied to evaporation from water surfaces in the 1920's and 1930's, was applied to crop surfaces by Penman and Budyko in the 1940's. Penman combined an energy balance and aerodynamic equation into what is commonly known as the combination equation which is now used in modified forms extensively throughout the world (Penman, 1948).

The modern irrigation scheduling programs which evolved from these early experiments consist of six primary steps (Fig. 7). First, an inventory of the soil and crop characteristics for each field is made to gain an understanding of the essential requirements for efficient irrigation. Then a calculation of the water needs of the growing crops is made, specifically at what rates are the crops and soil surfaces utilizing water from the soil moisture reservoir. Such estimates are generally based on well tested empirical techniques, rather than actual measurements, because of convenience and the established reliability of the computational procedures. The next aspect of irrigation scheduling is to determine the availability of moisture in the root zone for meeting crop needs between irrigations. This step is accomplished by initially sampling the soil profile to measure the available soil moisture storage, and then periodically sampling to re-assess the available moisture and update the consumptive use estimates. Upon determining the amount of soil moisture available, the interval between irrigations is projected. In addition, by knowing the soil and irrigation system characteristics, the amount of water to be applied (as well as the means to accomplish the suggested application) can be determined. Finally, the results of the previous steps must be delivered to the irrigator in order to implement the suggestions. This program is subsequently repeated throughout an irrigation season.

ESTIMATION OF EVAPOTRANSPIRATION

Several techniques have been developed as means for estimating the evapotranspiration from growing crops including soil sampling, lysimeters, large scale hydrologic balances, pan evaporation, and empirical computational procedures. The two methods most used in scheduling programs are computational methods known as the Penman and Jensen-Haise methods. These procedures provide daily estimates using local climatological information. The accuracy varies according to the ability to represent meteorological conditions

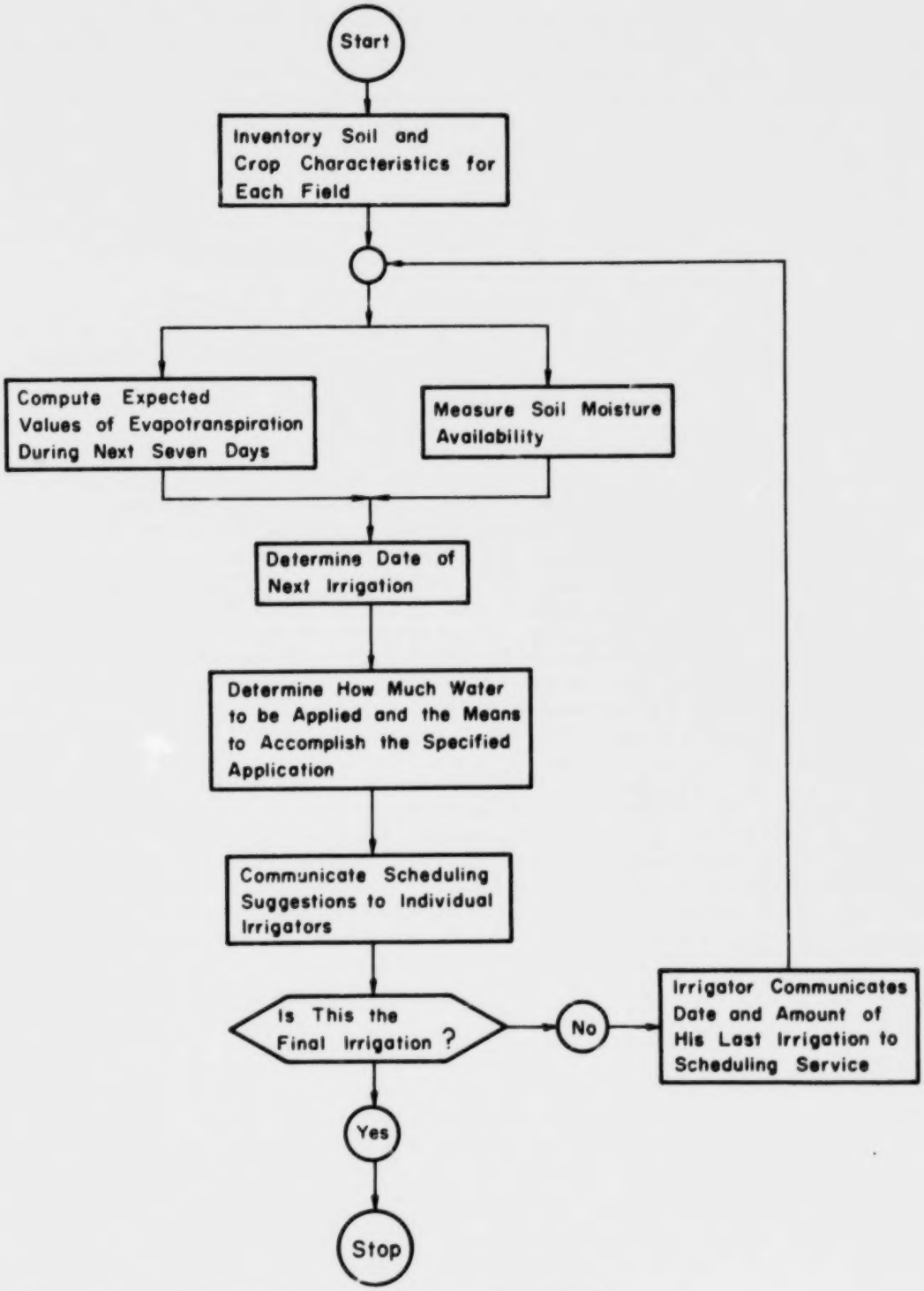
Start
Inventory Soil and Crop Characteristics for Each Field
Compute Expected Values of Evapotranspiration During Next Seven Days
Measure Soil Moisture Availability
Determine Date of Next Irrigation
Determine How Much Water to be Applied and the Means to Accomplish the Specified Application
Communicate Scheduling Suggestions to Individual Irrigators
Is This the Final Irrigation ?
No
Irrigator Communicates Date and Amount of His Last Irrigation to Scheduling Service
Yes
Stop

Fig. 7. Irrigation scheduling components.

properly, but generally the accuracy can be within 10 to 15% (Jensen, 1972).

Penman Equation

In 1948, Penman combined an energy balance equation with an experimentally derived aerodynamic function for water vapor movements to yield an expression for estimating the evaporation from an open water surface. The values determined from the relationship were multiplied by empirical constants to arrive at the evapotranspiration rates from well-watered grass. However, in 1963 Penman determined that by using a proper value of albedo ($\alpha = 0.25$), the potential evapotranspiration for grass could be evaluated directly.

The form of the Penman combination equation employed today can be written,

$$E_{tg} = \frac{\Delta}{\Delta+\gamma} (R_n+G) + \frac{\gamma}{\Delta+\gamma} (15.36)(1.0 + 0.0062u_2)(e_z^\circ - e_z) \quad ..(1)$$

in which E_{tg} is the potential evapotranspiration in cal cm^{-2} day^{-1} from a well-watered short-grass surface, Δ is the change in saturation vapor pressure with temperature in mb deg^{-1}, γ is a property of dry air in mb deg^{-1}, R_n is the net radiation in cal cm^{-2} day^{-1}, G is the sensible heat flux to the soil in cal cm^{-2} day^{-1}, u_2 is the wind speed at a height of two meters expressed in miles per day, e_z° is the saturation vapor pressure in mb for atmospheric conditions z meters above the crop surface, e_z is the existing vapor pressure in mb at a height of z meters, z is the height at which the wind velocity is actually measured.

The terms in Eq. 1 may not be readily available, thus requiring additional computations. First, the terms $\Delta/(\Delta+\gamma)$ and $\gamma/(\Delta+\gamma)$ can be calculated, but are usually expressed in convenient tables such as shown in Table 2. Net radiation, R_n, is determined either by direct measurement or by the relationship,

$$R_n = (1 - \alpha)R_s - R_b \quad . . . . . (2)$$

where α is the albedo (usually = 0.225-0.25 for green crops), R_s is the solar radiation in cal cm^{-2} day^{-1} which is generally measured, and R_b is the net outgoing thermal radiation in cal cm^{-2} day^{-1}. The value of R_b is calculated with the regression expression,

Table 2. Variation of $\Delta/(\Delta+\gamma)$ with elevation and temperature.

Temp. °C	-6.7	-1.1	4.4	10	15.6	21.1	26.7	32.3	37.8
Temp. °F	20	30	40	50	60	70	80	90	100
Elevation (ft)	Values of $\Delta/\Delta+\gamma$								
0	.296	.377	.461	.534	.620	.687	.745	.794	.833
2000	.309	.392	.477	.559	.634	.700	.757	.804	.842
4000	.324	.408	.493	.576	.649	.714	.769	.814	.851
6000	.339	.425	.500	.592	.665	.728	.781	.824	.859
8000	.357	.444	.530	.610	.682	.743	.794	.835	.868
10,000	.376	.464	.551	.630	.699	.758	.807	.846	.877

$$\frac{\gamma}{\Delta+\gamma} = 1 - \frac{\Delta}{\Delta+\gamma}$$

$$R_b = \left[a\left(\frac{R_s}{R_{so}}\right) + b \right] R_{bo} \quad \ldots\ldots\ldots\ldots \quad (3)$$

in which a and b are the regression coefficients usually taken as 1.0 and -0.2 for arid areas respectively, R_{so} is the clear day solar radiation taken from existing charts and expressed in cal cm^{-2} day^{-1}, and R_{bo} is the clear day net outgoing thermal radiation in cal cm^{-2} day^{-1} calculated by,

$$R_{bo} = \left(a_1 + b_1\sqrt{e_d}\right)\left(11.71 \times 10^{-8}\right) T_k^4 \quad \ldots\ldots \quad (4)$$

where a_1 and b_1 are again empirical constants (0.39 and -0.042 in arid regions), e_d is the saturation vapor pressure at mean dew point temperature in mb, and T_k is the average daily temperature, °K. The final parameter in Eq. 1—wind speed at two meters—is generally not available at this height. Therefore, the wind speed at two meters can be approximated by the following logarithmic relationship,

$$u_2 = u_z \ (2/z)^{0.2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

in which u_z is the wind speed in miles per day at a height of z meters.

Upon generating the value of E_{tg}, an equivalent depth can be determined by multiplying by 0.00171 to obtain mm/day and by 0.000673 to obtain in/day.

Although the Penman relationship includes most of the parameters affecting evapotranspiration rates and is sensitive to a wide variety of climatic changes, it remains primarily a tool for experimental work. Data for the function must be collected in sites representative of the crop surfaces being evaluated, thus requiring instrumentation needs far beyond the capability of most agricultural areas. However, as part of large irrigation scheduling services, instrumentation for these data needs are often justifiable in terms of reliability and consistency.

Jensen-Haise Method

The second method which is of great use in irrigation scheduling programs is the Jensen-Haise Method of estimating

evapotranspiration. In 1963, Jensen and Haise re-evaluated about 3,000 published and unpublished short-period measurements of evapotranspiration based on soil sampling procedures during a 34-year period in the western United States (Jensen and Haise, 1963). These data were correlated with solar radiation (the main component of the energy balance equation) and mean air temperature in order to develop an equation for potential evapotranspiration. Potential evapotranspiration as used here represents the upper limit, or maximum, evapotranspiration under given climatic conditions that occurs within a field having a well-watered crop of alfalfa with about 12 to 18 inches of top growth. The equation to compute this potential evapotranspiration is,

$$E_{ta} = C_T(T - T_x)R_s \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

where C_T is an air temperature coefficient which is constant for a given area and is derived from the long term mean maximum and minimum temperatures for the month of highest mean air temperature, T is the daily mean temperature, T_x is a constant for a given area, R_s is daily solar radiation expressed as cal cm^{-2} day^{-1}, and E_{ta} is the potential evapotranspiration of the alfalfa, in cal cm^{-2} day^{-1}.

When accurate evapotranspiration data are available for an area, C_T and T_x can be determined by calibration. When the data are not available, then the coefficients are estimated by empirical equations. The equation for the temperature coefficient C_T is,

$$C_T = \frac{1}{C_1 + C_2 C_H} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

where C_H is a humidity index and is evaluated as follows,

$$C_H = \frac{37.5 \text{ Hg}}{e_2^\circ - e_1^\circ} = \frac{50 \text{ mb}}{e_2^\circ - e_1^\circ} \quad \ldots\ldots\ldots\ldots \quad (8)$$

in which e_2° is saturation vapor pressure in mm Hg (or in mb) at mean maximum air temperature during the warmest month and e_1° is the saturation vapor pressure at mean minimum air temperature during the same month. The value of C_1 is found as follows:

$$C_1 = 68°F - (3.6°F \times \text{elevation in feet}/1000 \text{ feet}) \quad \ldots\ldots \quad (9)$$

The value of C_2 is 13°F (or -10.6°C) while the coefficient T_x is calculated as:

$$T_x = 27.5°F - 0.25(e_s - e_a)°F/mb - (elev./1000\ feet)°F \quad (10)$$

The equation coefficients are primarily a function of specific areas and are adjusted for elevation to correct for differences in atmospheric pressure, which affects vapor pressure values.

Although this method is simpler to use in a scheduling program because it requires less meteorological data than the Penman equation, it may be somewhat less sensitive to climatic changes such as windy weather. A comparison of the Penman and Jensen-Haise methods (both adjusted and unadjusted for elevation at the Grand Valley) with pan evaporation data for the Grand Valley area is presented in Fig. 8 from data supplied by the Bureau of Reclamation. It should be remembered in viewing Fig. 8 that the estimates represent evapotranspiration from different surfaces. Thus, the Jensen-Haise (both standard and adjusted) is for well-watered alfalfa, while the Penman is for short grasses. The variation in the Jensen-Haise methods with altitude should be carefully examined since the existing practices in Grand Valley suggest the elevation corrections introduce, rather than correct, error. However, a recently released study at an altitude of 10,000 feet indicates the elevation correction is accurate and, therefore, deserves further evaluation (Kruse and Haise, 1974).

EVALUATION OF SOIL MOISTURE

Water provides the structural integrity of the plant tissues, as well as performs an important role in the transport of nutrients throughout the plant body. Within the soil-water-plant system, a liquid phase provides a continuous link between soil, plant, and atmosphere. The details characterizing soil-water-plant relationships are far too vast to describe herein, rather a brief review of some of the more important aspects will be touched upon. Specifically, the aspect of the soil-water-plant system of primary interest in this study is the soil water availability.

The availability of soil moisture is governed by several important parameters including (Buckman and Brady, 1969):

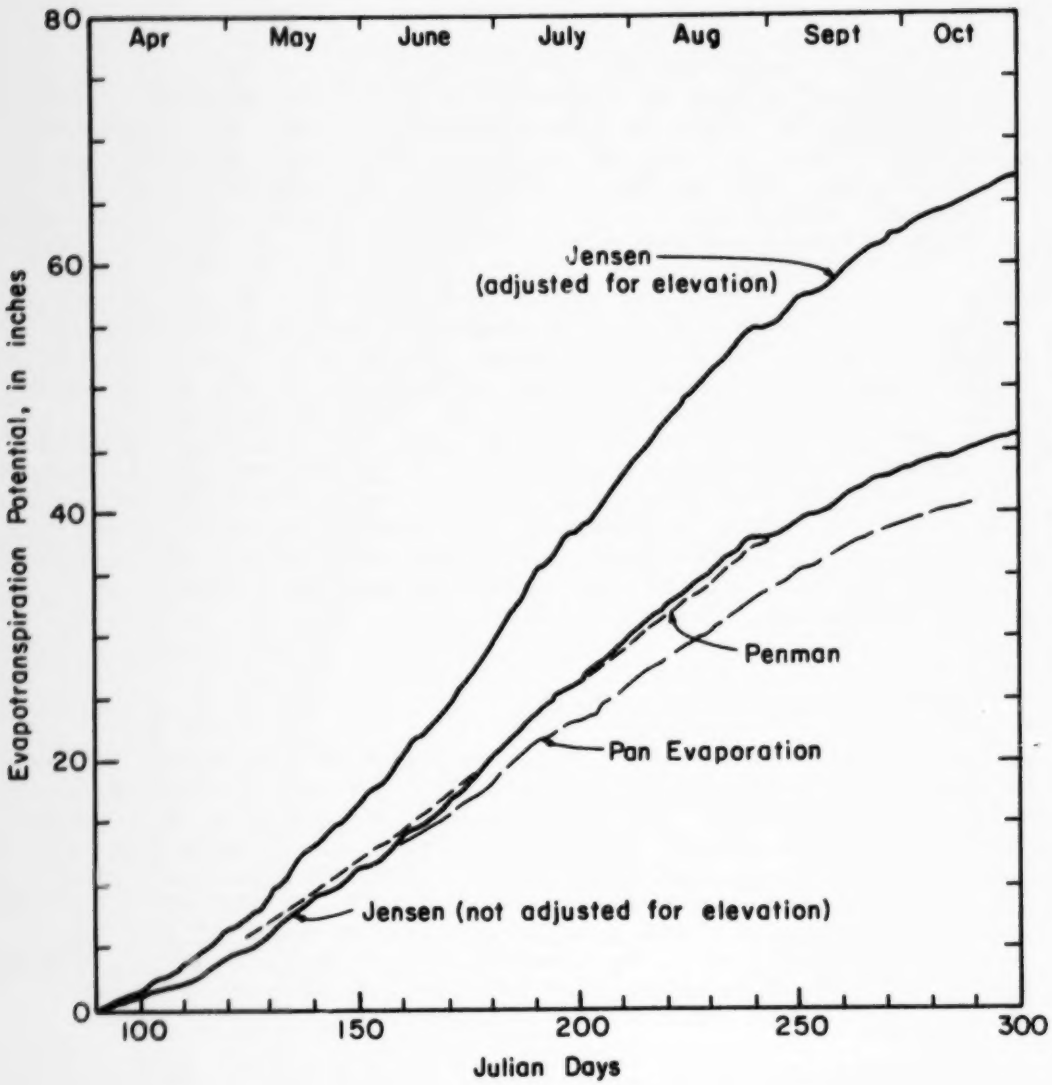

Fig. 8. Cumulative potential evapotranspiration in Grand Valley for 1973 irrigation season.

1. Soil texture, structure, and organic matter, all of which affect the moisture tension relationship;

2. Osmotic potentials governed by the solutes in the soil solution and the rates of evapotranspiration; and

3. Soil depth included within reach of the plant root system.

Soil texture determines to a large extent the amount of water which can be stored in the profile for use by crops and the rates with which water enters and moves through the soil. Fine textured soils, those with high clay contents, hold much more moisture than do coarse textured soils such as those with high sand contents. In addition, the coarse soils drain faster and thus require more frequent irrigation and greater care with respect to the quantities applied. The moisture generally available for use by the plants is usually taken as the difference between field capacity and the wilting point. However, to avoid placing stress on the crops, irrigations are usually scheduled when the available soil moisture is depleted by 50% (Buckman and Brady, 1969).

The size and shape of the soil aggregates play an important role in the productivity of different soils, by affecting the ease with which roots penetrate the soil, along with the rate at which water enters and moves through the soil. Soils with poor structure impede the intake of water into the soil and consequently reduce the water available for the plants. Soil structure also affects the moisture holding capacity and the distribution of roots. Often, farming practices which are not suitable for the local soils will reduce yields by diminishing the soils capability to optimally support crop growth.

The percentage of organic matter in the soil and its influence on moisture holding capacity has been the subject of debate for a number of years. In the Central Valley of California, several studies were made on soils with various quantities of organic matter added to the soil. The conclusions drawn from these studies indicated that although large additions of organic matter did in some cases increase field capacity percentage, they also raised the wilting point percentage; hence little affect on the additional available moisture capacity was realized (Willardson, 1972). Other studies were made which stated that the quantity of water that soils can hold in a form available for plant use is influenced by both the quantity of clay and organic matter in the soil. In general, soils which are low in clay and organic matter have low water holding capacities, while

soils having large amounts of these materials usually have increased capacities for holding water. Sandy soils show appreciable increases in available storage capacity when increased amounts of organic matter are used.

Among the more influential parameters which affect the soil water availability are those which affect the osmotic potential. Probably the most critical of these factors is the concentration of dissolved salts in the soil water. As the salt concentration increases, the osmotic potential must increase to extract the moisture from the soils such that the wilting point may vary quite widely from its usual value of -15 bars. In severe cases, the moisture content of the soil must be maintained near field capacity to allow sufficient water uptake by the crops. A typical plot of the salinity effects on osmotic potential is illustrated in Fig. 9.

Another of the primary factors affecting the rate of crop transpiration is the osmotic potential as demonstrated in Fig. 10. From this illustration, it is important to note that irrigation scheduling should vary allowable soil moisture depletion percentages to reflect the rates of water uptake by the plants.

Finally, a soil parameter having a pronounced effect on a scheduling program is the depth of soil penetrated by the root system. Soils which allow deep penetration by roots increase the volume of the soil moisture reservoir available to crops. In addition, the nutrient resources are more effectively utilized, (if sufficient nutrients are not available near the ground surface), thereby increasing crop yields. As the season progresses, rooting depths increase on the annual crops, resulting in more available water and plant nutrients.

The amount of soil moisture that has been depleted from the root zone is determined by using gravimetric techniques, or a "feel" method with a corresponding chart. Although the sampling is more accurate, it requires more time to take the samples and weigh them, dry them, and calculate a value. The percent depletion is then obtained by interpolating between the wilting point moisture content and field capacity. The other method, which is quicker but less accurate, is the "feel" method used by the Bureau of Reclamation. The moisture depletion is determined by taking a sample with an Oakfield probe and manipulating it in the hand and observing whether it will make a ball or a ribbon of certain length, thus fixing the moisture depletion. The depletion is determined either from charts such as illustrated in Table 3, or by calculation. In the latter case, the summation of the evapotranspiration minus the summation of effective

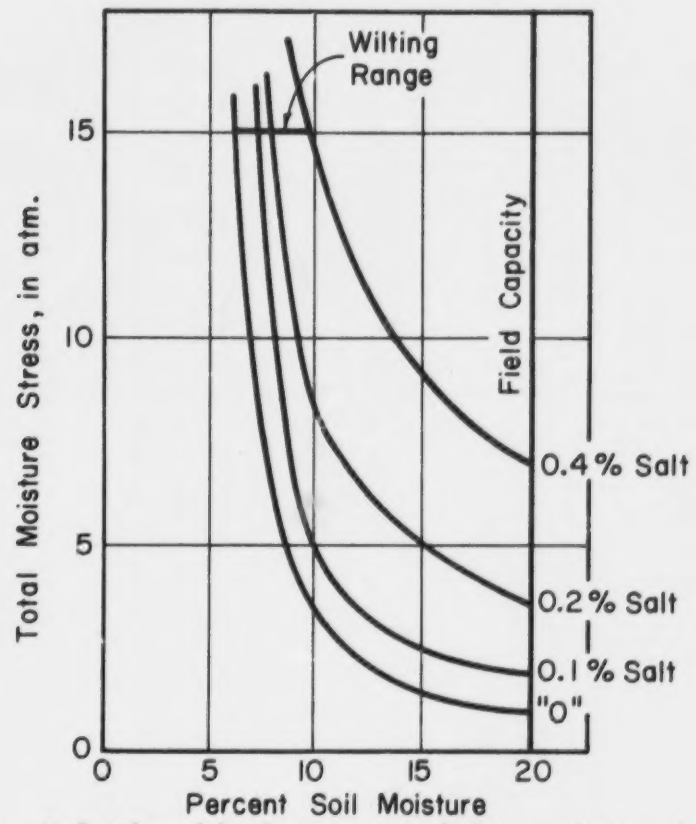

Fig. 9. Relationship between moisture stress to moisture percentage at different levels of soil salinity.

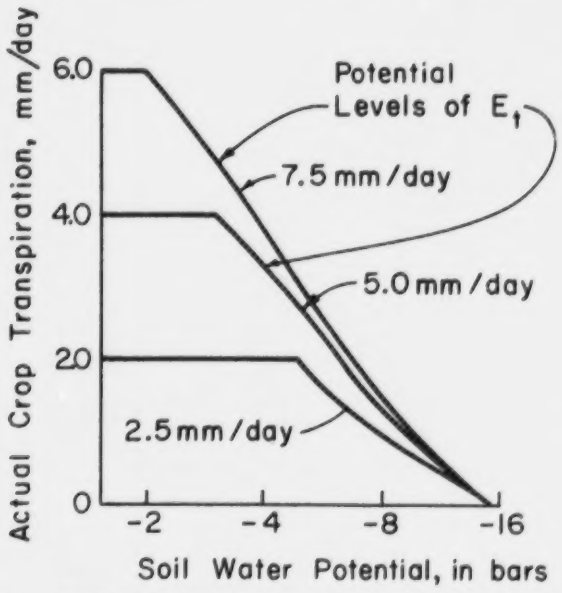

Fig. 10. Relationship between crop transpiration rates and soil water potential.

Table 3. Chart for estimating percent depletion of readily available soil moisture by feel.

Per Cent Depletion	Feel or appearance of soil by general texture groups		
	LIGHT Loamy fine sand-fine sandy loam	MEDIUM Very fine sandy loam-silt	FINE AND VERY FINE Sandy clay loam-clay
100-75	Dry, loose, flows through fingers	Powdery, dry, will not form a ball.*	Hard, baked, cracked sometimes has loose crumbs on surface.
75-50	Appears to be dry will not form a ball.*	Dry almost powdery. A ball can be formed under pressure. The ball is very crumbly and hardly holds its shape. Will not ribbon; soil too crumbly.**	Somewhat pliable. Will ball under pressure.*
50-25	Tends to ball under pressure but seldom holds together.	Forms a pliable ball. Soil doesn't stick to hand. No moisture on hand just damp feeling. Ribbons readily. Soil has no slick feeling.	Forms a pliable ball. Ribbons readily. Soil sometimes has a slick feeling.
25-0	Forms a weak ball, breaks easily, has no slick feeling.	Forms tight plastic ball; slightly sticky. Ribbons easily; solid. Slick feeling with moist particles left on hands.	Easily ribbons out between fingers; has a slick feeling.
0 (Field Capacity)	Upon squeezing no free water appears on soil but wet outline of ball is left on hand.	Same as light.	Same as light.

* Ball is formed by squeezing a handful of soil firmly.
** Ribbon is formed by squeezing soil out between thumb and forefinger.

Supplied by Bureau of Reclamation, Grand Junction Projects Office

rainfall which occurs during the period of interest is the moisture depleted from the root zone. A promising alternative to these methods, generally limited to research studies, is the use of neutron probes which are calibrated by gravimetric sampling. This method generally is the most accurate because of the consistency of the measurements.

PREDICTING SUBSEQUENT IRRIGATIONS

The expected date of the next irrigation is determined by knowing the maximum allowable depletion of soil moisture, M_o, the depletion which has occurred to date, M_d, and the average expected evapotranspiration, $\bar{E}_t$, for the three preceding days and the three forecast days. The number of days N till the next irrigation is calculated by,

$$N = (M_o - M_d)/\bar{E}_t \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

where N equals 0 if $M_d \geq M_o$.

In many cases, an estimate of how much water to apply per unit of area is just as important (or more important) as knowing the date of the irrigation. This estimate can be obtained as follows:

$$W_a = M_o/E_f \quad M_o \leq M_d \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

$$W_a = M_d/E_f \quad M_d \geq M_o \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

where W_a is the total depth of water per unit area to be delivered to the field; and E_f is the farm efficiency which is the percentage of water supplied to the farm that is consumptively used. The amount of water that must be applied to the root zone will be determined by the method of irrigation which the farmer uses and his skill and willingness to apply water efficiently to reduce the losses below the root zone (deep percolation) and the tailwater runoff from the field. The irrigation scheduling program utilized by the USBR in Grand Valley is depicted in Table 4.

IRRIGATION SCHEDULING REQUIREMENTS

As a summary of this section, the authors would like to discuss the requirements for successful irrigation scheduling programs in the light of an overall salinity control objective. In previous segments of this section, the

Table 4. USBR irrigation scheduling service in Grand Valley.

DATE OF COMPUTER UPDATE — June 7, 1971 (Update 3) — COMPUTER UPDATE NUMBER

SECTION A

Recorded Daily Climatic Data and Potential Evapotranspiration for the Update Period

1	2	3	4	5	6
Date	Ave. Temp. Deg.F	Solar Rad. In./D	Daily ETP. In./D	Effect Precip Inches	Wind Run Miles
601	49.5	.37	.20	.00	70.0
602	52.0	.40	.23	.00	30.0
603	50.5	.41	.23	.00	90.0
604	45.0	.40	.19	.00	90.0
605	46.5	.41	.20	.00	120.0
606	47.0	.21	.10	.00	5.0

SECTION B

Forecast Potential Evapotranspiration Inches Per Day

1	2	1	2
Date	ETP. In./D	Date	ETP. In./D
607	.29	614	.31
608	.30	615	.32
609	.30	616	.32
610	.30	617	.32
611	.30	618	.32
612	.31	619	.32
613	.31	620	.33

FARM NAME — SAMPLE FARM — FARM NUMBER — Farm Code 2

SECTION C

Irrigation Scheduling--Field Status as of June 7, 1971

1 2 3	4 5	6	7	8	9	10	11	12	13	14	15	16
Fld Code Crop and Size Ac.	Dates Plant & Cover	Crop Coef Ave	RT ZN FT	Soil Type	Hold Cap. Inch	Allow Depl. Inch	Depl Moisture Beg	Soil End	Irrigations Last Date	Last Amt in.	Next Date	Next Amt in.
1 Pas 40	505 605	.87	3.0		3.8	2.7	.0	1.0	518	1.8	613	3.7
2 Alf 47	510 710	.69	8.5	Silt L	10.4	7.3	.0	.1	519	1.5	701	11.5
3 WHE 22	514 720	.24	2.0		2.6	1.0	.0	.5	520	3.5	612	1.5

essential aspects of a scheduling program included determination of evapotranspiration rates, soil moisture availability, and intervals between irrigations of specified application. In addition, the communication of data between irrigator and scheduler was noted. When these tasks are integrated in a manner that maximizes the efficiency with which a farmer applies water to his land, an effective irrigation scheduling program is considered implemented.

In order to achieve any reduction in the salt load reaching the Colorado River, irrigation scheduling must accomplish more than just specifying a quantity of irrigation water to be applied at a specific date. The quantity of irrigation water applied must result in reduced deep percolation losses. Therefore, the problem at hand is to determine the essential elements of an irrigation scheduling program that will minimize deep percolation losses.

SECTION V

FIELD INVESTIGATIONS

EXPERIMENTAL DESIGN

The efficiency with which water is utilized by the irrigators in the Grand Valley varies widely, depending on soil and crop factors as well as the skill and concern applied by the farmer to each irrigation. Since the more acute salinity problems are traceable to the most inefficient irrigation practices, irrigation scheduling as a salinity control measure will also exhibit a wide range of effects. The principle aim of this project is directed towards establishing this range of effectiveness. In order to successfully evaluate irrigation scheduling as a salinity control alternative, the scope of the project has included a more detailed examination of segments of the hydro-salinity system. Specifically, such parameters as soil, crop, and field characteristics, along with irrigation efficiencies, surface and groundwater outflows, and root zone moisture and salt movements are of special concern.

To accurately describe the important variables in the study, the design of the field investigations were formulated into three phases. The first phase was continued monitoring of essential water and salt movements within the hydrologic framework surrounding the farming environments. Next, an effort was made to evaluate some of the operational problems inherent in implementing irrigation scheduling on croplands in the valley. This aspect of the study was included to provide some experience regarding actual field problems on farms in serious need of structural rehabilitation and improved water management. The primary emphasis of the study was centered in the final phase which involved a concerted effort to evaluate the on-farm factors determining the effectiveness of irrigation scheduling.

In this section of the report, a description of the field work undertaken to accomplish the three work phases will be presented. Since the study involved a great deal of data collection and analysis to arrive at the final results, a representative sample will be periodically included so the reader will develop some appreciation for the results. Some of the data is descriptive of the more significant segments of the hydro-salinity network throughout the valley and thus serves as a good illustration of these conditions. Hopefully, the inclusion of some field data will provide a smoother transition between this section and the presentation of the findings in the following section.

AREA HYDROLOGY

Most of the extensive instrumentation employed during the initial evaluation of canal and lateral linings was maintained and utilized during this project. Since the scope of this study was altered slightly to facilitate the project objectives, this data collection effort was generally reduced. The measurements of canal inflows and outflows were discontinued, and the measurements of drainage discharge, piezometer fluctuation, and subsurface exploration were reduced. During the years of investigations in the area, project personnel were able to equip substantial laboratory facilities for detailing the chemical characteristics of both soil and water. In this project period, the number of samples analyzed was expanded to provide a broader basis for stating the chemical quality characteristics of the area. Among the additional samples collected and analyzed were those taken from the local canals and ditches which were compared to data published in the U. S. Geological Survey surface water records.

Groundwater Movements and Quality

The analysis of data collected from wells extending into the cobble aquifer indicates the magnitude of the flows returning to the river, as well as the salts being transported as dissolved minerals. The well installations, numbering 17 in all, were located throughout the test area as part of the earlier investigations.

Evaluations made earlier indicate that the regional effectiveness of a salinity control program will be manifested primarily in the hydraulic characteristics of the aquifer. A comparison of data relating the hydraulic conductivities of both the area soils and the aquifer indicate that the cobble is many times more permeable than the upper soils. Since the soils and cobble are generally saturated and exhibit only slight differences in hydraulic gradients, nearly all of the subsurface return flows are occurring in the cobble aquifer. Within the period of study in the area, the water levels in the wells have not varied significantly over the annual cycle. For example, data from two wells, one near the river (Well No. 3) and the other (Well No. 12) two miles further north, have been plotted in Fig. 11 to illustrate both the seasonal and annual variation. The changes in hydraulic gradient occurring during the period of this study can be evaluated by dividing the elevation differences by the distance between the two wells. For example, at the maximum and minimum points during each year, the hydraulic gradients are shown on Fig. 11. It is apparent

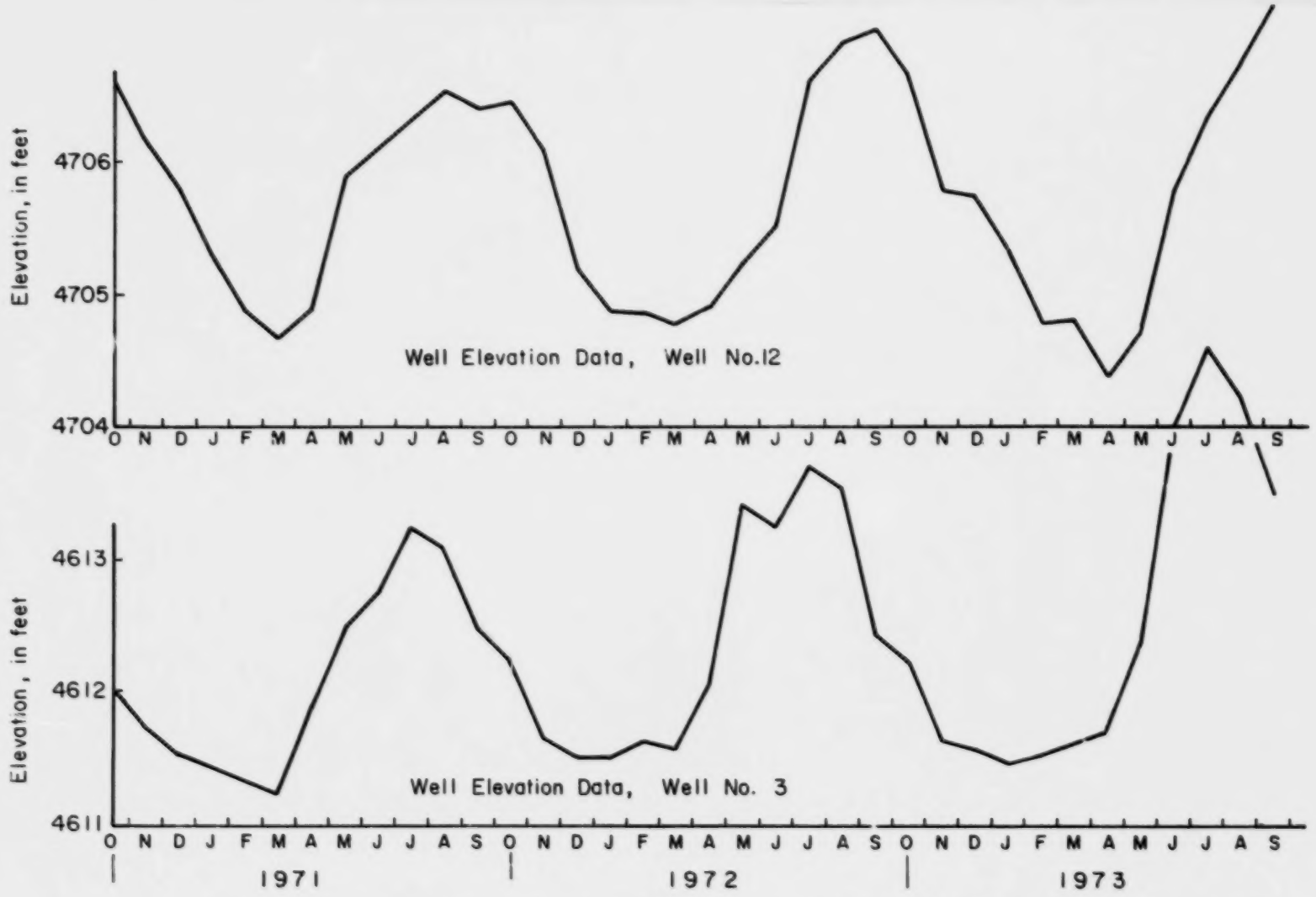
Elevation, in feet
4706
4705
4704
Well Elevation Data, Well No.12
O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
Elevation, in feet
4613
4612
4611
Well Elevation Data, Well No. 3
O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1971
1972
1973

Fig. 11. Seasonal variation of water levels in two wells monitoring the cobble aquifer.

that the minimum and maximum points for each well occur at different times, pointing out the time lag which may exist as the water flows from one point to another. Another important observation is that the hydraulic gradient changes only 5-8 percent during the season; and over the three years of available data, the variation was small.

The water quality samples taken from these wells are the most conclusive demonstration of the salt pickup occurring in the Grand Valley. A summary of data collected from Well No. 3 near the Colorado River, presented in Table 5, indicates several important characteristics of the flows being evaluated by the wells. The value of total dissolved solids in this well range between 6,000 ppm and 8,000 ppm with an average of about 6,700 ppm. The ratio between the concentration of TDS and specific conductance for the irrigation water ranges between 0.6 to 0.7, but the data from the well indicates a ratio of about 1.09. This abrupt change is due to the high sulfate content of the groundwater. Well quality data also depict the effect of irrigation in Grand Valley upon specific salt constituents being added to the Colorado River. Skogerboe and Walker (1972) reported that the average cation composition of the irrigation water in terms of meq/l is 41% calcium, 24% magnesium, 34% sodium, and 1% potassium. Data in Table 5 indicate an average of 25% calcium, 43% magnesium, 31% sodium and 1% potassium. The examination of anionic constituents is even more revealing in that the percentage of sulfate increases from 58% in the irrigation water supply to 79% in the groundwater return flows.

Drainage Outflows

The combination of tight soils and a ground slope of between 1 and 2 percent results in a large percentage of the farm irrigation applications being wasted as field tailwater. These flows, along with groundwater intercepted by the drainage system, were measured with one-foot or two-foot Cutthroat flumes and nine-inch Parshall flumes. Each drain conveying flows from the study area was continuously monitored by equipping the flumes with stilling wells and water level recorders. Water quality samples were also collected periodically from these drains in order to evaluate the linkage between surface and subsurface hydrology.

The flows recorded during this study indicate that the principal use of the drainage system is for conveying field tailwater to the Colorado River. For example, the seasonal variation in discharge for one of the most significant drains, shown in Fig. 12, indicates a very rapid change which corresponds to the beginning (April 1) and end

Table 5. Selected water quality from Well No. 3 in the test area.

Sampling Date	TDS (ppm)	EC (µmhos/cm)	Cations				Anions				Analysis* Error
			Ca^{++} (ppm)	Mg^{++} (ppm)	Na^{+} (ppm)	K^{+} (ppm)	HCO_3^{-} (ppm)	Cl^{-} (ppm)	$SO_4^{=}$ (ppm)	NO_3^{-} (ppm)	(%)
10-30-69	6664	5900	447	513	750	17	586	332	3525	163	2
11-26-69	5904	4592	485	533	720	18	593	328	3525	137	3
2-05-70	7780	6136	409	528	650	17	600	328	3063	90	5
5-12-71	6400	5900	461	498	637	14	122	158	4055	62	0
6-22-71	6648	6800	477	440	1,030	15	409	111	5380	157	9
7-20-71	6500	6000	487	512	317	14	593	299	3170	149	4
8-02-71	6584	6335	822	770	495	17	583	306	3540	130	12
3-27-72	6604	6401	461	498	713	15	534	309	3696	130	0
7-10-72	6796	6489	471	522	644	13	583	304	3240	124	3
8-01-72	6884	6507	431	516	736	13	586	302	4512	126	9
9-14-72	6612	6533	551	474	725	14	581	330	3552	129	1
10-03-72	6476	6522	521	456	684	14	564	278	4560	114	11
11-15-72	6524	6381	377	586	644	15	583	307	3648	114	0
1-02-73	6472	6240	481	492	667	14	647	313	3888	122	4
1-29-73	6504	6355	451	571	690	14	683	342	4032	124	3
3-05073	6544	6355	488	520	753	17	622	488	3696	127	1
4-02-73	6476	6355	561	437	782	16	647	362	3600	119	10
4-30-73	6408	5720	471	504	748	10	884	300	3504	105	10
7-02-73	8356	5497	400	426	729	12	659	400	3024	114	10
7-30-73	5573	5140	486	460	600	10	598	328	3168	139	10
Average	6679	6094	488	513	686	14	583	311	3719	129	1%

* Error= $\dfrac{(\Sigma\text{cations} - \Sigma\text{anions})}{\left(\dfrac{\Sigma\text{cations} + \Sigma\text{anions}}{2}\right)} \times 100.0$

Note - Σcations and Σanions are expressed in meq/l.

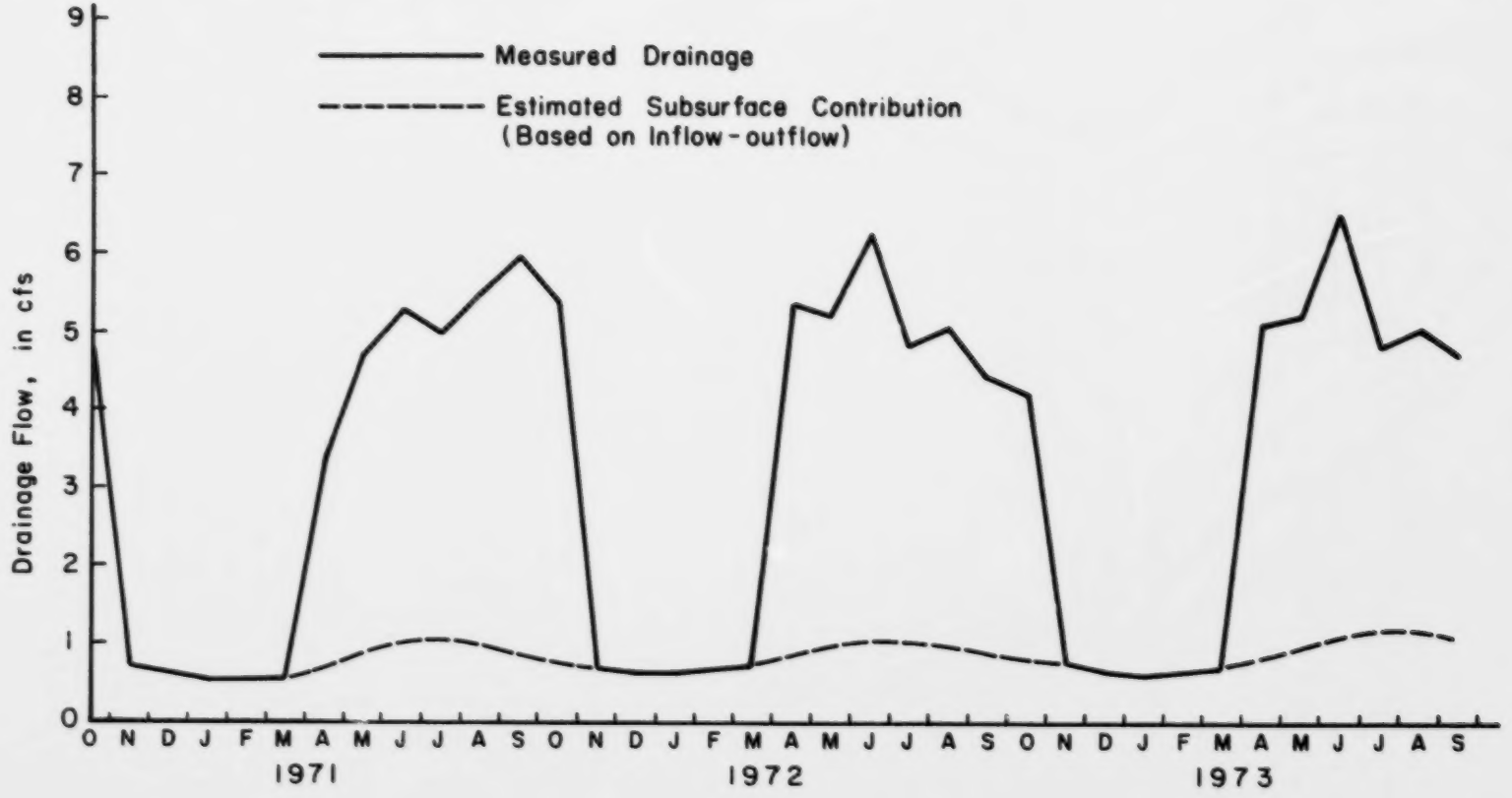

Fig. 12. Seasonal and annual drainage flows for a selected drain in the test area.

(October 31) of the irrigation season. The fraction of these flows which can be attributed to either groundwater interception or field tailwater is identified by the water quality of the flows (Table 6). In comparing salinity levels before and after the end of the irrigation season, it is apparent that field tailwater accounts for about 80-90 percent of the flows in this drain.

Quality of Irrigation Water

As a means of rapid identification of certain segments of the salt flow system near the farm environment, periodic sampling for water quality was undertaken on the flows being diverted for irrigation. Since these data, with the exception of the Mesa County Ditch, do not differ significantly from the data collected by the U. S. Geological Survey at the local river stations, a summary will not be presented herein. Water for the Mesa County Ditch consists primarily of spillage from the Grand Valley Canal into Lewis Wash along with spillage from other canals, tailwater return flows, and groundwater. Thus, the quality of irrigation water supplied to croplands under the Mesa County Ditch is significantly deteriorated as indicated by Skogerboe and Walker (1972).

Use of Data

Earlier reports by Walker (1970) and Skogerboe and Walker (1972) employed canal, drain, and groundwater flow data to arrive at segmented budgets of the hydrology in the project area. These studies were based on other investigative efforts and modeling programs. Certain of those earlier results have been employed to extend conclusions to the broader context of the entire Grand Valley, with good correlation.

For the purposes of this study, a recalculation of budgets for the project area will not be made, because the effect of irrigation scheduling can be established from the data previously presented. For example, each acre-foot of water entering the groundwater can be expected to return to the river containing 6,000 to 8,000 ppm of total dissolved solids. Some of the salt in these flows are those initially carried by the irrigation water, so the magnitude of salt pickup is a fraction of the range noted above. Rather than using flows and concentrations to determine salt pickup as was done previously, data relating quantities of salts will be used.

Table 6. Summary of water quality data taken from a drain in the test area.

Sampling Date	TDS (ppm)	EC (μmhos/cm)	Ca^{++} (ppm)	Mg^{++} (ppm)	Na^{+} (ppm)	K^{+} (ppm)	HCO_3^{-} (ppm)	Cl^{-} (ppm)	$SO_4^{=}$ (ppm)	NO_3^{-} (ppm)	Analysis* error (%)
3-04-69	8056	5973	471	529	425	16	403	340	3000	186	2
5-15-69	2428	2282	128	141	290	8	215	144	1175	1	2
6-11-69	2148	1951	120	117	200	5	200	100	913	41	3
6-30-69	1340	1897	134	85	195	6	205	92	850	16	3
8-12-69	2388	2615	144	161	356	11	268	192	1275	27	1
9-02-69	2724	2349	164	129	270	9	288	184	1275	40	10
10-28-69	1596	1180	196	73	245	6	234	148	900	38	1
12-31-69	7588	7168	489	503	975	18	547	324	4050	128	2
2-05-70	7880	7100	491	547	950	16	493	326	4050	5	4
6-08-70	2492	2564	168	140	225	7	257	155	840	54	5
6-15-70	1788	2000	160	92	260	2	254	41	973	40	1
7-27-71	1392	1856	88	117	162	7	207	115	750	30	3
8-12-71	956	2277	170	79	251	7	257	194	913	39	6
7-11-72	1692	2163	140	107	230	5	215	127	780	39	3
7-31-72	2868	3264	207	182	451	9	288	187	1368	74	6
9-04-72	2256	2714	176	129	319	8	261	207	1008	42	2
10-03-72	1700	2342	152	100	253	8	251	160	1008	29	5
11-15-72	7472	7151	417	567	909	14	517	310	4608	94	3
1-02-73	7548	7269	371	577	960	13	659	313	4176	141	0
1-29-73	7692	7246	461	492	932	13	610	367	4464	165	5
3-05-73	7608	7200	581	378	1144	16	561	427	4086	36	1
4-12-73	7368	7175	581	431	1093	16	599	322	4464	165	1
4-30-73	1660	2057	124	104	260	6	415	139	816	29	0
7-02-73	1460	1816	154	61	87	5	232	62	640	32	8
7-30-73	1680	2081	115	92	275	5	232	122	804	24	0
Average[1]	1916	2200	149	112	255	7	252	139	958	33	
Average[2]	7651	7035	483	503	924	15	549	341	4112	115	

[1]Average of irrigation season samples
[2]Average of non-irrigation season samples

$$*\text{Error} = \frac{(\Sigma\text{cations} - \Sigma\text{anions})}{\left(\frac{\Sigma\text{cations} + \Sigma\text{anions}}{2}\right)} \times 100.0$$

Note - Σcations and Σanions are expressed in meq/l

FACTORS AFFECTING IRRIGATION SCHEDULING

Since the purpose of this phase of the project was to evaluate irrigation scheduling as a salinity control measure, two farms were selected upon which a detailed analysis of the factors affecting the success or failure of scheduling irrigations was undertaken. In accomplishing this work, three divisions in the analysis developed. The first of these was the efforts to understand the operation of the individual farms. Secondly, several investigations were undertaken to determine the field characteristics describing the inter-relationships between water management and salinity. Finally, water and salt budgets were developed using data collected over two years of study.

Field Descriptions

The two farms, (Bulla and Martin farms), represent contrasting farming practices in an area where farming is not the primary source of income. The Bulla farm was incorporated into this study to represent the valley-wide conditions rather than local water management practices. Careful attention is given to the details of farming since this field, along with several others, is the primary enterprise of the farmer. Because of the well operated nature of the farm, soil conditions are well maintained allowing a variety of crops to be grown including tomatoes, corn, barley, and sugar beets. The agricultural variety of this farm is particularly significant because the investigators have been able to evaluate a wide range of agricultural conditions. The Bulla farm, shown in detail in Fig. 13, consists of about 25 acres of land supplied with water from a diversion from the Price Ditch to the north. Excess irrigation water supplied by a concrete head ditch at the northern boundary of the field results in field tailwater, which is removed from either corner at the southern boundary and then flows into the Grand Valley Canal.

During all of the years that the Martin farm, shown in Fig. 14, has been investigated, the 8.5-acre field has been cultivated exclusively in corn silage. This farm is one part of a 200-acre farming operation conducted by Mr. Don Arnold through a rental agreement with several local land owners. As a result, the time spent in irrigating this field has been minimized in order to facilitate the overall efficiency of the total enterprise. These conditions presented a unique opportunity during the 1973 irrigation season, as the renter agreed to turn the irrigations of the Martin farm over to the project personnel. Thus, while the Bulla farm represented intensive analysis of an existing practice, the

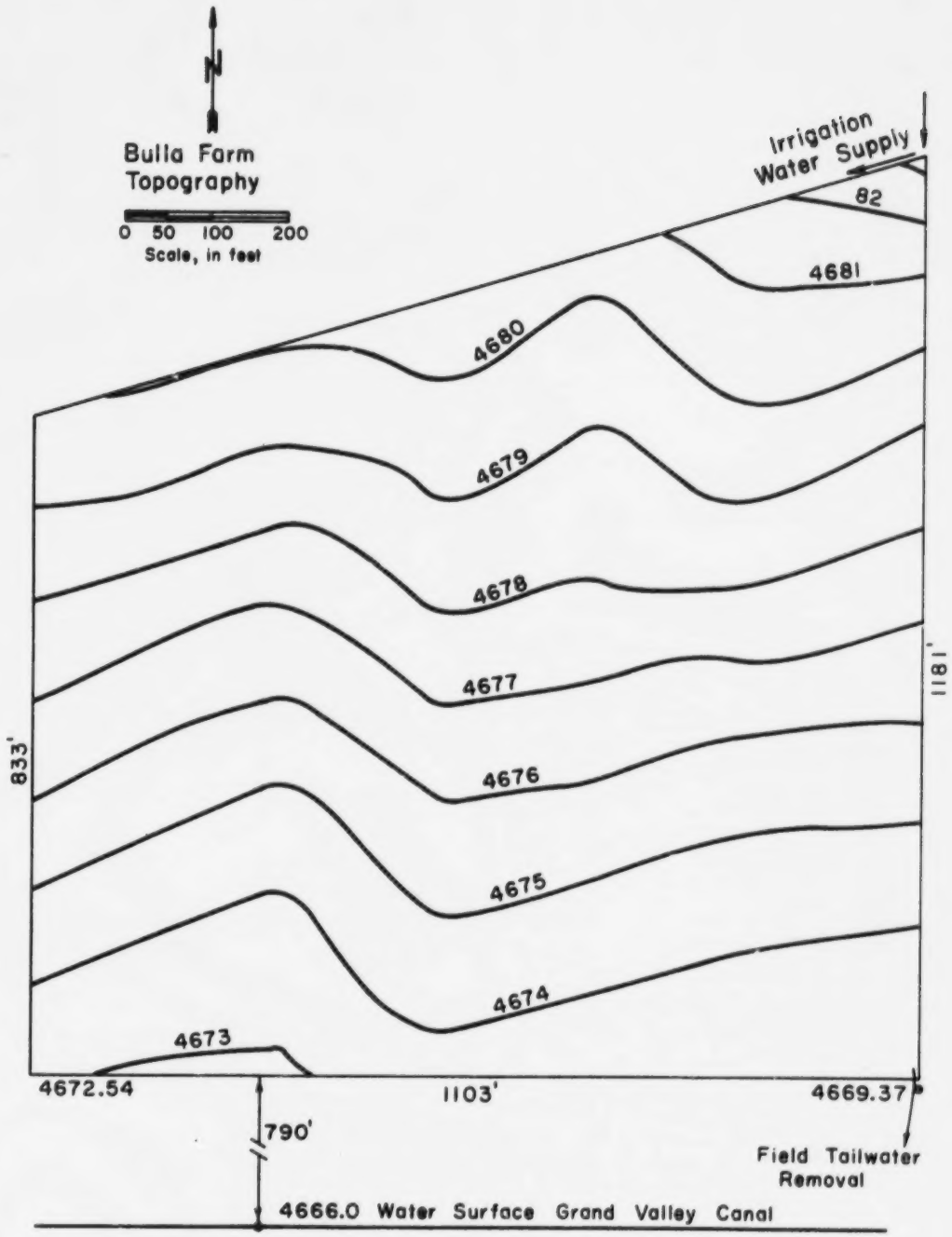

Fig. 13. The Bulla farm layout.

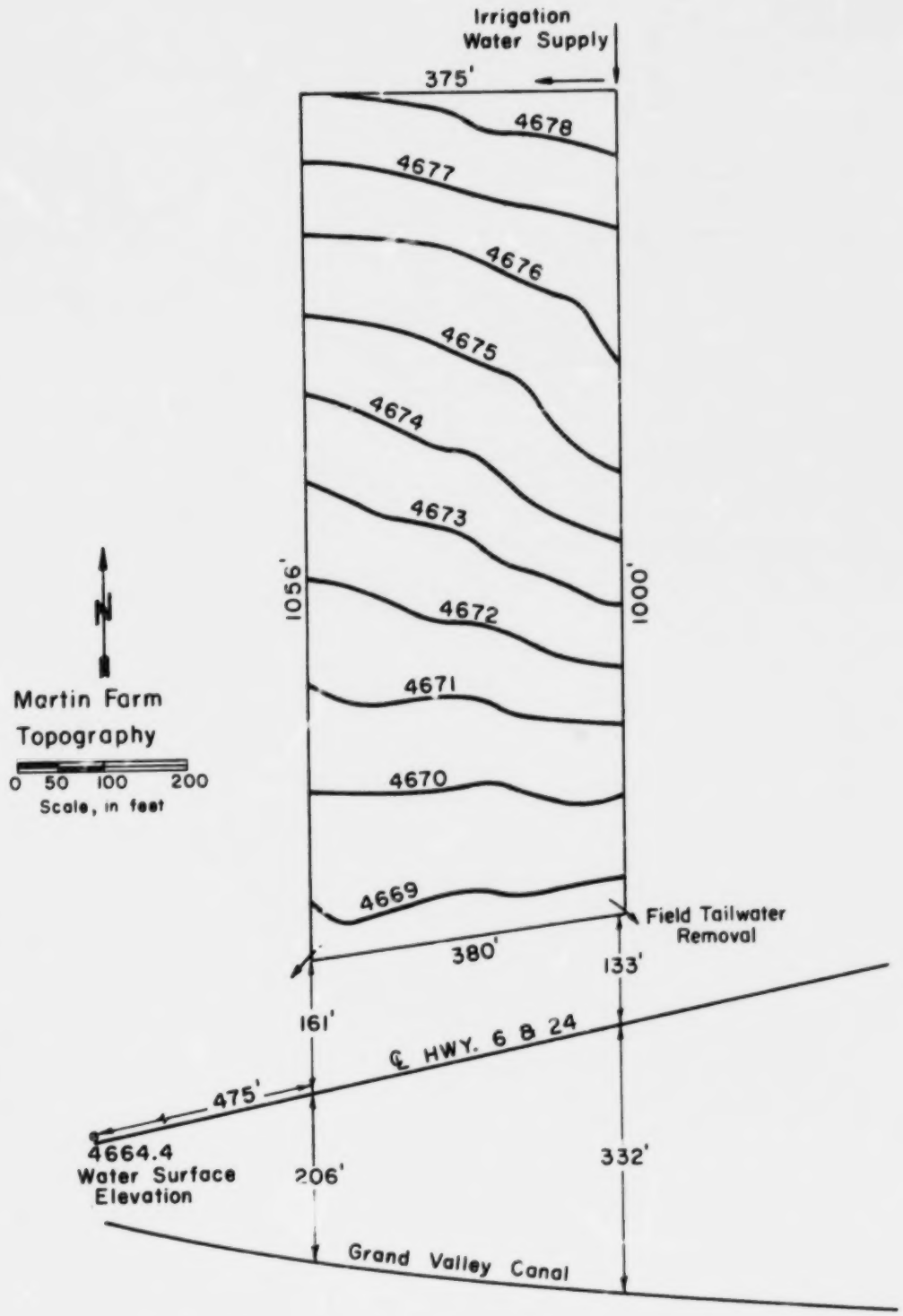

Fig. 14. The Martin farm layout.

Martin farm allowed the investigators to explore the potential of various irrigation procedures.

Field Characteristics

In an effort to expand the scope of this study beyond simply evaluating existing on-farm water management practices, the investigators studied several of the important characteristics of each farm to see where improvements might be made to increase irrigation efficiencies. In addition to the inflow and outflow measurements, other parameters evaluated included soil intake rates, furrow advance rates, field levelness, and field water table elevations and chemical quality of surface and subsurface flows.

The procedure employed to determine intake rates involved carefully measuring the water into and out of a 200-foot section of furrow with the time-varying differences recorded. Then, the data are formulated into intake rate functions as shown for two tests in Fig. 15. Intake rates vary considerably throughout the irrigation season reflecting changes in soil conditions and tillage practices. Generally, intake rates were shown to decrease significantly as the season progressed, indicating the necessity to modify irrigation practices during the season.

Furrow advance rates, described by Skogerboe and Walker (1972), were determined for a wide range of furrow flow rates during this study. One hundred foot intervals were marked along a furrow, with the time being recorded for the flow to traverse each interval. The results, illustrated for a typical set of data in Fig. 16, have only cursory value in this study, but do indicate some interesting facts concerning the time water should be left in the furrows during each irrigation set. For example, suppose a furrow on the Bulla farm is supplied with about 8.5 gpm in which the advance rate and intake functions are similar to the functions shown in Figs. 15 and 16. After about five hours under normal conditions, the flow would have reached the end of the field and began wasting a fraction to field tailwater. If the flow is to remain in the furrow 24 hours, then the fraction of the flows resulting in root zone applications and field tailwater can be computed.

An example of these results can be plotted to demonstrate the decisions a farmer may face in operating his irrigation system to maximize returns from the land. In Fig. 17, a cumulative intake is plotted against time for typical early and late season conditions. During the initial stages of an irrigation, the bulk of the water is applied to the root

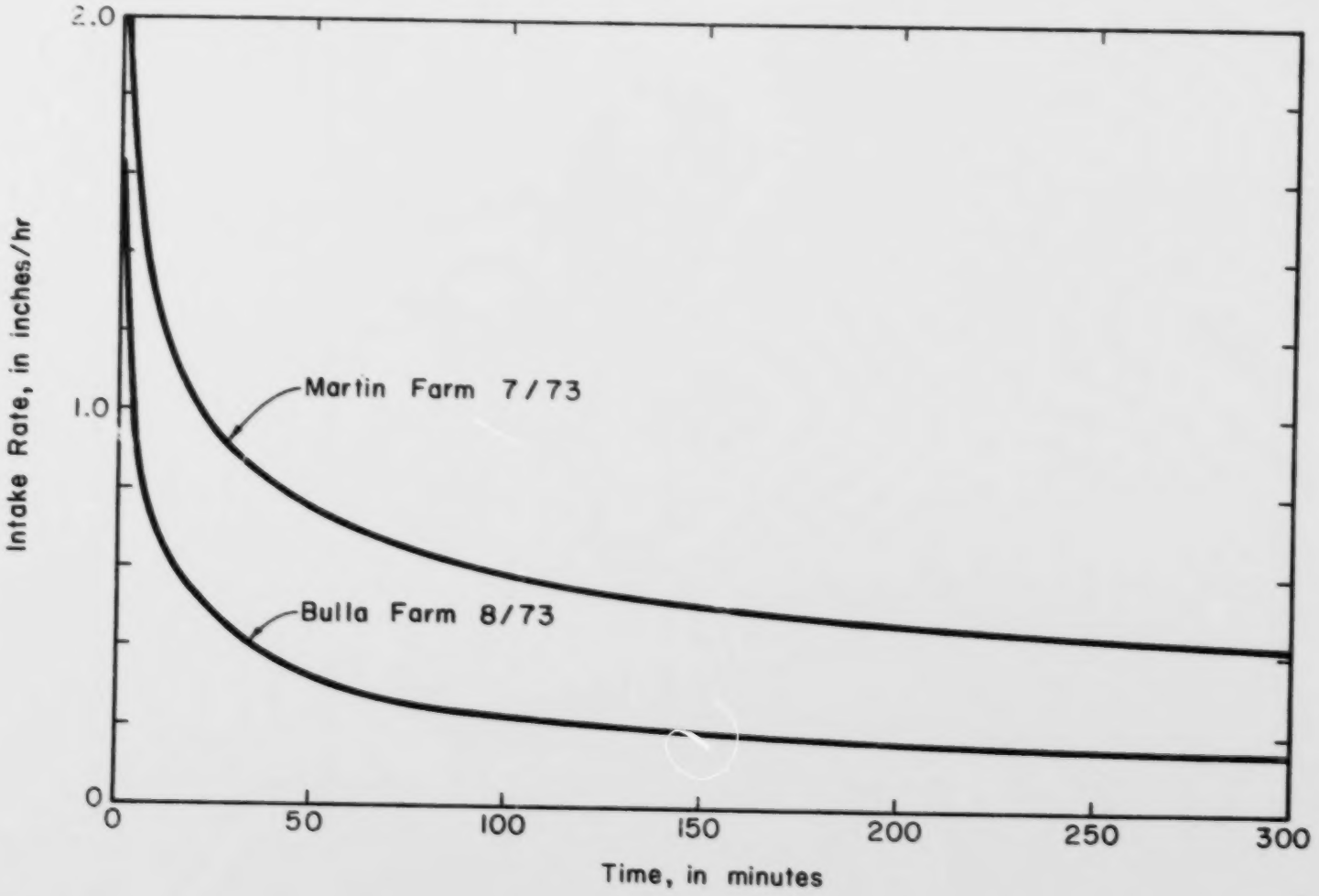

Fig. 15. Typical intake rates for the soils in the test area.

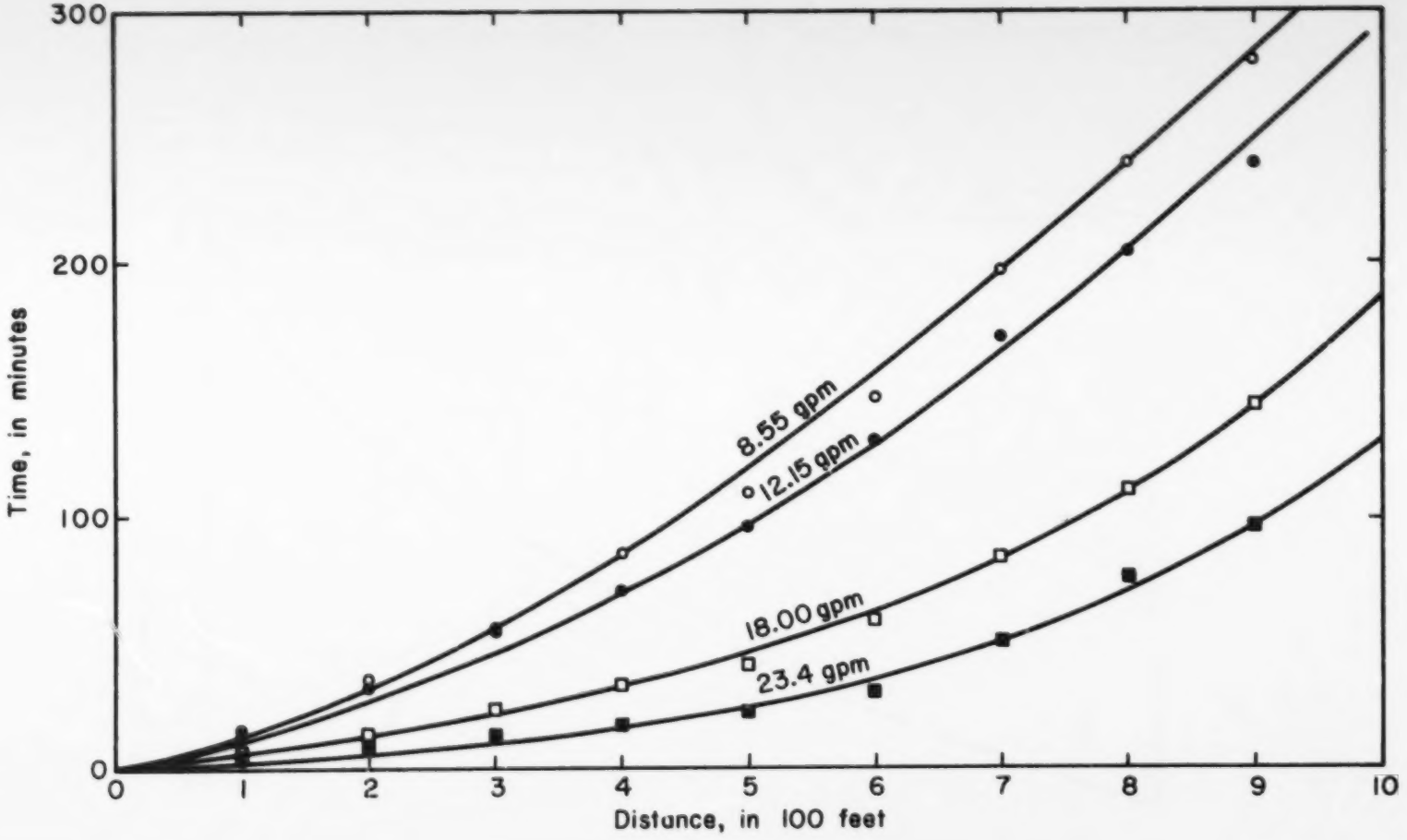

Fig. 16. Typical furrow advance curves on the Bulla farm.

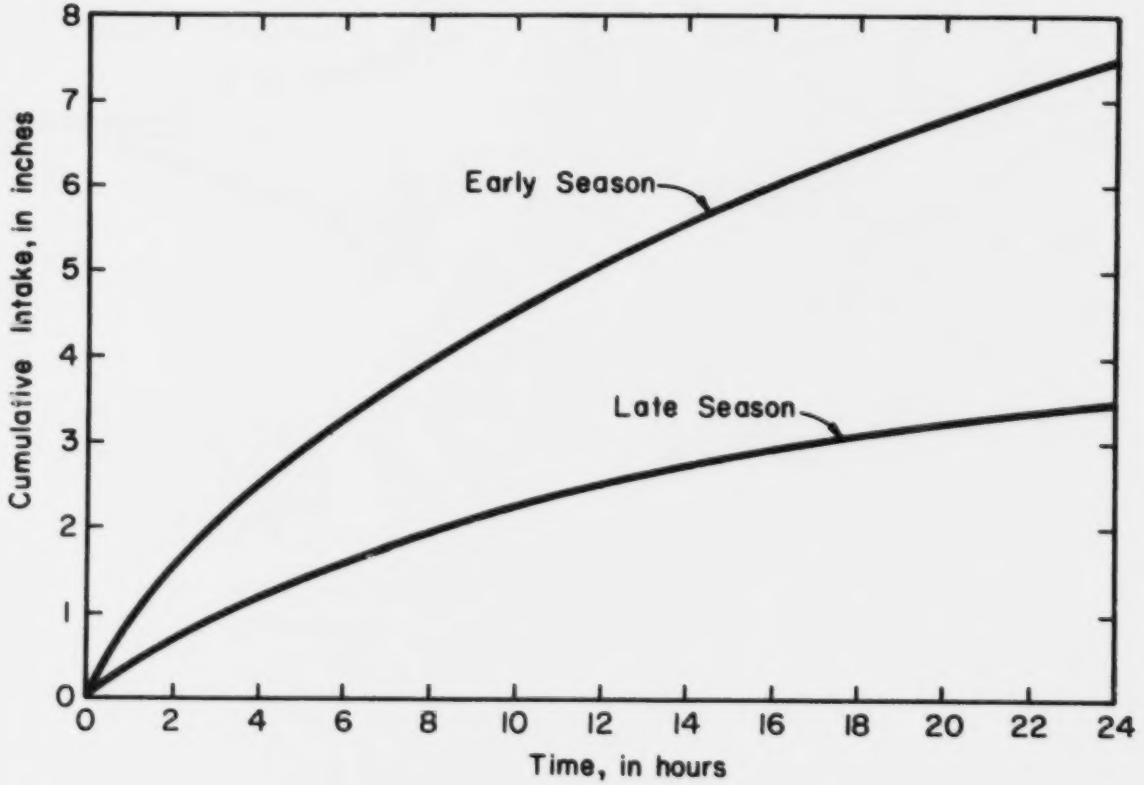

Fig. 17. Cumulative intake functions for early and late irrigations in the test area.

zone. As the irrigation progresses, less and less water infiltrates the soil surface, thereby resulting in most of the flow being field tailwater.

These results also indicate possible methods for improving the effectiveness of irrigation scheduling as a salinity control measure by allowing the farmer to apply the proper amounts of water to his soil by regulating the time that water is allowed to remain in each furrow. For example, suppose an early irrigation requires that only 5.5 inches be added to the root zone storage in the field. If the length of each irrigation set is reduced from 24 to 12 hours, the deep percolation loss can be reduced from 2.5 inches to 0.3 inches. Thus, a great deal of salinity control would be realized.

In addition to evaluating soil characteristics, a new dimension to this study was the observation of water table levels and water quality within the farm confines. An example of the elevation data, shown in Fig. 18, illustrates the season variations of the on-farm water table heights. In budgeting the root zone flows and monitoring water table elevations around the farm, is was obvious that much of the variations were due to changes in the groundwater system outside the fields. The quality of the farm water tables averages about 2000-3000 mg/l less than deeper groundwater flows, thereby suggesting the qualitative nature of the salt pickup system. It may be worth noting, however, that the effects of poor field levelness is apparent on the Martin farm as the quality of groundwater under the upper and lower ends of the field is 7000-8000 mg/l higher (i.e., 15,000-16,000 mg/l TDS) than the aquifer flows pointing to the possibility of poor leaching.

Irrigation Efficiencies

For the purpose of this study, irrigation efficiency has been divided into two more specialized measures of efficiency; namely, farm efficiency and application efficiency. Farm efficiency is defined as the percentage of the water supplied to the farming confines which was either consumed by the crop or stored within the root zone for subsequent use. This measure of efficiency represents the overall effectiveness of the irrigator in using his water supply on his land. Application efficiency is the percentage of the water entering the environment of the root zone which is used by the crop or remains in root zone storage. This efficiency is intended to demonstrate the adequacy of the irrigation system in supplying the crop with suitable moisture. The difference between the two efficiencies is that

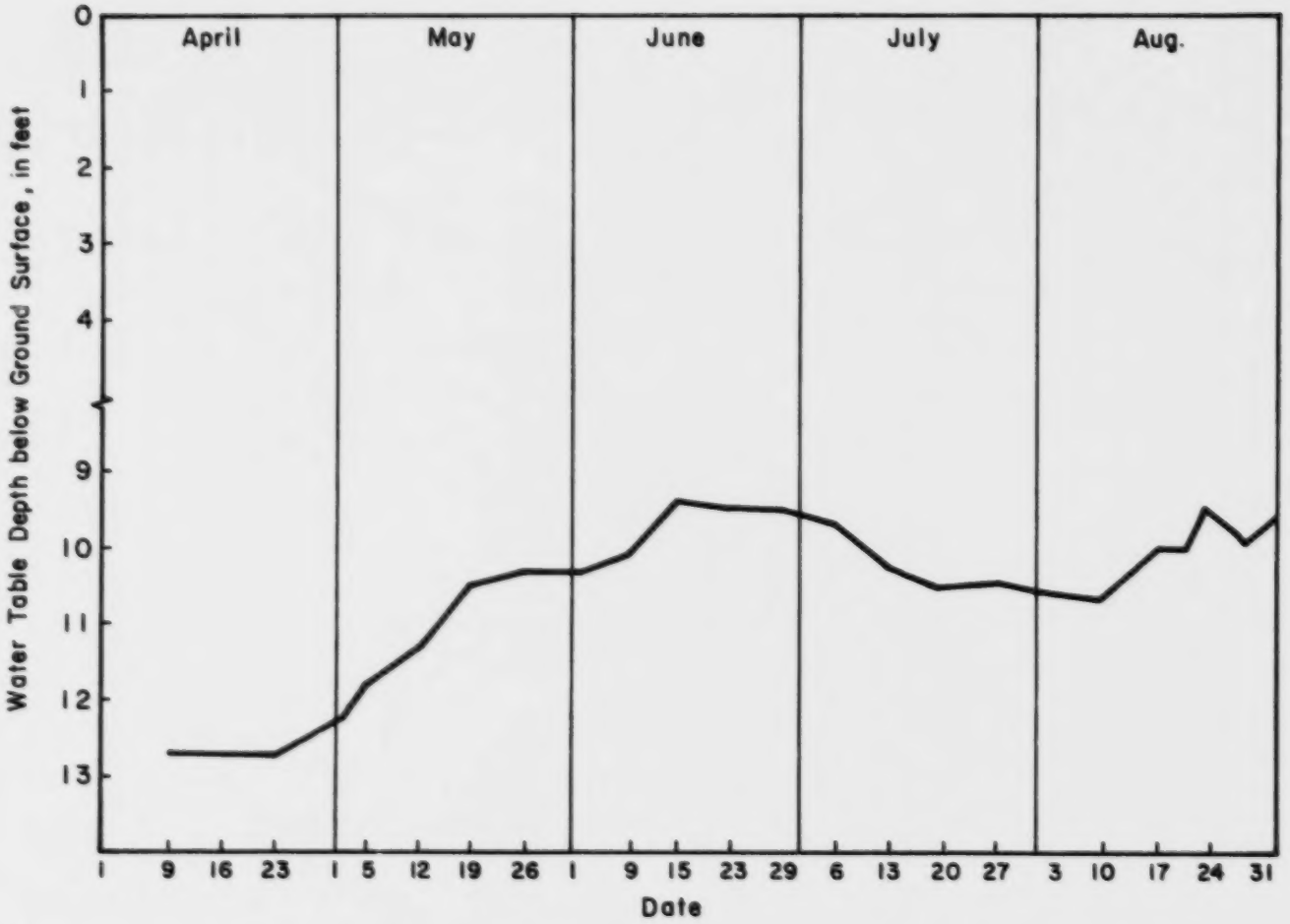

Fig. 18. Seasonal variations in water table elevations on the Bulla farm during 1973.

the latter does not account for field tailwater or seepage from the field head ditch.

To determine values for either measure of efficiency, it is necessary to measure inflows, outflows, and soil moisture storage as well as calculate evapotranspiration. Deep percolation is determined as the residual in a water budgeting procedure. The inflows to the fields and the field tailwater were continuously measured with recorder equipped Parshall flumes on either end of the field. The calculated difference between the two flows during an irrigation period is the quantity of water applied to the root zone. Once within the root zone, the water is either consumed by the crops, percolates below the root system, or remains in storage. To account for this delineation, soil moisture samples were taken before and after each irrigation. The quantities of water transpired by the crops or evaporated from soil surfaces were calculated by the methods described in the previous section.

Based upon these data, water and salt budgets for the farm environment were prepared. Farm and application efficiency were then determined for each irrigation, as well as seasonal averages in order to evaluate the variation of these efficiencies throughout the irrigation season.

From the derived water and salt budgets, the effects of irrigation scheduling can be ascertained. For example, the relative effects of early irrigation are shown in the budgets and can be compared with later water application efficiencies to determine where improvements are most needed.

SECTION VI

RESULTS OF SCHEDULING EVALUATION

In the Grand Valley, irrigation scheduling along with field drainage, conveyance channel linings, structural rehabilitation of the irrigation system, and non-structural incentives for better water management appear to be the most feasible array of salinity control alternatives. Of these measures, irrigation scheduling may yield the most substantial results because of the large number of parameters in the hydro-salinity flow system which are influenced. Two years of evaluating irrigation scheduling have produced several important results with respect to salinity control in the area which logically divide into the conclusions derived from the study and the recommendations for strengthening the impact of irrigation scheduling. These two segments will be developed in this section by first presenting an analysis of the water and salt budgets and then detailing the requirements for successful irrigation scheduling in the valley.

ANALYSIS OF WATER AND SALT BUDGETS

Budgeting Procedure

During this study as in those previous, the investigators have identified the water and salt flows in terms of budgets as a means of evaluating the impact of improvements. The budgets generated for this study are narrow in scope and include only the irrigated field from the head ditch and wastewater ditch to the bottom of the root zone (assumed to be four feet). For each irrigation and the periods between the water flows are determined. This process gives a complete budget accounting for each budget interval and thus allows the results to be examined in more detail. Because of the scope of this evaluation, the budgets presented are primarily of the water flows with the salts described only in the context of salt pickup from deep percolation.

The budgets to be presented in the following pages include four segments: (1) Farm Inflows; (2) Root Zone Water Budget; (3) Irrigation Efficiencies; and (4) Salt Pickup. In the following paragraphs, the discussion will focus upon the definition of these budget items and note the data from which they are identified.

Inflows to the farm take the form of either diversions from irrigation canals and ditches or effective precipitation

(moisture added to the root zone). These flows are applied to the crop surfaces and subsequently infiltrate into the soil or become surface runoff from the field into waste ditches or drains. Each of the inflows to the field and the surface outflows are measured as described in the previous section.

The root zone water budget accounts for moisture within the reach of the crops. A depth of four feet was assumed to encompass this region even through root depths often exceed this value at maturity. Since the crops being grown on the two farms were corn, sugar beets, and barley, the assumed depth is not unreasonable. The first segment of the root zone budget is the total water additions determined by combining the water supplied by an irrigation with effective precipitation. It should be noted that groundwater might also be available to the deep rooting crops such as alfalfa, although not to the two farms in this study. The moisture supplied to the root zone replenished the soil moisture storage reservoir. The change in this storage volume is determined from soil moisture sampling at the beginning and end of each budget interval. During the budget interval, the crops transpire water which is calculated using the Jensen-Haise method for estimating evapotranspiration. Finally, the residual flow, deep percolation, is arrived at through a mass balance.

As a means of applying these results to the broader context of the Grand Valley, two measures of irrigation efficiency were defined earlier. The first of these, farm efficiency, is the percentage of the farm water supply utilized by the crops. Thus, farm efficiency is the consumptive use minus the root zone storage change divided by the total root zone addition plus field tailwater. Because farm efficiency values are affected by both the quantities of field tailwater and deep percolation, it serves as a general indication of water management on the farm. The second measure, application efficiency, is the percentage of the root zone addition utilized by the crops and thus is determined by the formula for farm efficiency except that field tailwater is omitted from the denominator. Consequently, application efficiency describes the suitability of the irrigation design and the irrigation practices.

The final item in the budgets is the expected salt pickup resulting from the deep percolation losses. These values are determined by comparing the quantity of salts carried by the irrigation diversions with the quantity in the groundwater as discussed in the previous section. Samples from the local canals and the U. S. Geological Survey samples from the river inflows were compared with well data

such as that presented previously in Table 5. It should be noted that values in Table 5 are slightly low with respect to the average groundwater qualities as determined by the wells.

The 1972 and 1973 water and salt budgets for the Martin and Bulla farms are presented in Tables 7, 8, 9, 10, and 11. For purposes of clarifying the budgeting procedures, some numerical segments from the tables can be abstracted for demonstration. Consider first the initial irrigation on the Martin farm during the 1972 irrigation season (Table 7). Flows passing the inlet flume were recorded as 129.48 acre-inches, while the flows passing the two field exits were measured as 52.80 acre-inches, thereby leaving 76.68 acre-inches in the soil profile (root zone addition). During this period between April 18th and April 27th, 5.1 acre-inches of rain fell on the field of which three-fourths, or 3.83 acre-inches, were assumed effective in infiltrating the soil surface.

Of the 80.51 acre-inches of moisture added to the root zone region (irrigation plus precipitation) only a negligible amount evaporated from the surface because of climatic conditions and the crop had not yet emerged. However, the soil moisture samples indicated that 35.46 acre-inches had been stored in the root zone leaving 45.05 acre-inches as deep percolation.

If the two measures of efficiency as defined earlier are calculated, it is apparent that this first irrigation was highly inefficient in leading to 31.4 tons of salt being picked up. Specifically, the 76.68 acre-inches of moisture added by way of irrigation to the root zone transported 2.8 tons of salt (322 ppm) and the 45.05 acre-inches of deep percolation upon reaching equilibrium with the 6700 ppm groundwater would carry an expected 34.2 tons, or a net increase of 31.4 tons.

During the interval between April 27th and June 17th when no irrigations were made, the crops essentially drew water from the soil moisture reservoir. The intervals between irrigations often indicates additional unsaturated deep percolation, making the efficiency values in the analysis slightly optimistic.

Analysis of Irrigation Efficiencies

Probably the best indication of the effectiveness of a change in irrigation practices can be gained from analyzing irrigation efficiencies. During the two years of this

Table 7 . 1972 Martin farm water budget. (8.5 acres of corn)

Budget Item	BUDGET INTERVAL (All values in units of acre-inches) 4/18 to 4/27	4/27 to 6/17	6/17 to 6/28	6/28 to 7/5	7/5 to 7/12	7/12 to 7/17	7/17 to 7/24	7/24 to 7/31	7/31 to 8/8	8/8 to 8/21	8/21 to 9/10	Total
Farm Inflows												
Field Tailwater	52.80	0	21.60	10.00	0	12.36	0	12.59	17.52	54.12	0	180.99
Root Zone Additions	76.68	0	31.68	22.31	0	28.03	0	33.64	20.04	54.72	0	267.10
Precipitation (effective)	3.83	0	0	1.70	0	0	0	0	0	2.13	0.94	8.60
Root Zone Water Budget												
Total Additions	80.51	0	31.68	24.01	0	28.03	0	33.64	20.04	56.85	0.94	275.70
Consumptive Use	0	21.99	25.16	20.27	18.0	17.85	18,15	20.32	22.70	31.88	32.73	229.05
Storage Change	35.46	-22.13	-11.17	-10.96	-18.0	-3.40	-18.20	9.18	-5.53	14.79	-31.79	-61.75
Deep Percolation	45.05	0.14	17.69	14.70	0	13.58	0.05	4.14	2.87	10.18	0	108.40
Irrigation Efficiencies												
Farm Efficiency	26.6%	--	26.3%	27.4%	--	35.8%	--	63.8%	45.7%	42.1%	--	36.6%
Application Efficiency	44.0%	--	44.2%	38.8%	--	51.6%	--	87.7%	85.7%	82.1%	--	60.7%
Salt Pickup (tons)	31.4	0.1	11.8	9.9	0	8.9	0	1.7	1.0	4.4	0	69.2
(tons/acre)	3.69	0.01	1.39	1.16	0	1.05	0	0.20	0.12	0.52	0	8.14

Table 8 . 1973 Martin farm water budget. (8.5 acres of corn)

BUDGET INTERVAL (All values in units of acre-inches)

Budget Item	5/1 to 6/17	6/17 to 6/25	6/25 to 7/1	7/1 to 7/10	7/10 to 7/16	7/16 to 7/20	7/20 to 7/26	7/26 to 7/30	7/30 to 8/3	8/3 to 8/9	8/9 to 8/14	8/14 to 8/17	8/17 to 8/21	8/21 to 8/28	8/28 to 9/10	Total
Farm Inflows																
Field Tailwater	44.04	28.32	0	36.38	0	7.22	0	8.58	0	6.04	0	4.25	0	30.60	0	165.43
Root Zone Additions	70.08	33.36	0	23.97	0	8.67	0	9.01	0	9.78	0	6.38	0	36.89	0	198.14
Precipitation (effective)	22.27	0	0	0	2.21	3.86	2.94	0	0	2.76	0	0	0.64	0	0	34.68
Root Zone Water Budget																
Total Additions	92.35	33.36	0	23.97	2.21	12.53	2.94	9.01	0	12.54	0	6.38	0.64	36.89	0	232.82
Consumptive Use	20.00	12.32	13.02	24.10	14.26	7.36	10.38	11.33	7.68	12.00	8.00	5.40	6.28	7.17	2.92	162.22
Storage Change	6.38	3.06	-13.02	-3.82	-12.05	5.00	-7.44	-2.80	-7.68	0.54	-8.00	0.98	-5.64	24.72	-2.92	-22.69
Deep Percolation	65.97	17.98	0	3.69	0	0.17	0	0.48	0	0	0	0	0	5.0	0	93.29
Irrigation Efficiencies																
Farm Efficiency	19.3%	24.9%	--	33.6%	--	62.6%	--	48.5%	--	67.5%	--	60.0%	--	47.3%	--	35.0%
Application Efficiency	28.6%	46.1%	--	84.6%	--	98.6%	--	94.7%	--	100.0%	--	100.0%	--	86.4%	--	59.9%
Salt Pickup (tons)	47.0	12.5	0	1.8	0	0	0	0	0	0	0	0	0	1.6	0	62.9
(tons/acre)	5.53	1.47	0	0.21	0	0	0	0	0	0	0	0	0	0.19		7.4

Table 9 . 1972 Bulla farm water budget . (25.7 acres of sugar beets)

Budget Item	BUDGET INTERVAL (All values in units of acre-inches)												
	4/7 to 4/25	4/25 to 5/1	5/1 to 5/11	5/11 to 5/22	5/22 to 6/16	6/16 to 6/28	6/28 to 7/6	7/6 to 8/1	8/1 to 8/8	8/8 to 8/28	8/28 to 9/14	9/14 to 9/18	Total
Farm Inflows													
Field Tailwater	156.24	0	28.20	44.88	0	96.24	0	173.16	56.52	113.16	139.56	65.64	873.60
Root Zone Additions	226.32	0	24.60	135.36	0	65.76	0	312.48	69.60	113.76	73.20	60.84	1,081.92
Precipitation (effective)	3.83	0	0	0	12.15	0	0	5.67	0	6.75	2.97	0	31.37
Root Zone Water Budget													
Total Additions	230.15	0	24.60	135.36	12.15	65.76	0	318.15	69.60	120.51	76.17	60.84	1,113.29
Consumptive Use	18.06	5.51	10.58	22.33	110.97	80.00	72.63	223.29	58.32	137.16	90.72	31.32	860.89
Storage Change	16.20	-7.31	+11.00	+78.30	-103.00	-20.00	-75.00	+13.50	-15.66	-20.00	-20.00	+27.00	-114.97
Deep Percolation	195.89	1.80	3.02	34.73	4.18	5.76	2.37	81.36	26.94	3.35	5.45	2.52	367.37
Irrigation Efficiencies													
Farm Efficiency	8.9%	--	40.9%	55.8%	--	37.0%	--	48.2%	33.8%	50.1%	32.8%	46.1%	37.5%
Application Efficiency	14.9%	--	87.7%	74.3%	--	91.2%	--	74.4%	61.3%	97.2%	92.8%	95.9%	67.0%
Salt Pickup (tons)	139.2	1.3	1.7	22.5	3.1	1.6	1.7	47.5	17.1	0	0	0	235.7
(tons/acre)	5.42	0.05	0.08	0.87	0.12	0.06	0.07	1.85	0.67	0	0	0	9.18

Table 10. 1973 Bulla farm water budget. (15.0 acres of corn)

Budget Item	BUDGET INTERVAL (All values in units of acre-inches) 5/22 to 6/27	6/27 to 7/7	7/7 to 7/14	7/14 to 7/23	7/23 to 7/30	7/30 to 8/13	8/13 to 8/27	8/27 to 9/2	9/2 to 9/10	Total
Farm Inflows										
Field Tailwater	69.24	9.12	0	59.52	8.88	85.80	67.92	0	57.96	358.44
Root Zone Additions	52.30	36.36	0	58.80	9.84	120.24	84.48	0	74.88	436.90
Precipitation (effective)	19.50	0	2.60	12.20	0	4.50	1.05	0	0.45	40.30
Root Zone Water Budget										
Total Additions	71.80	36.36	2.60	71.00	9.84	124.74	85.53	0	75.33	477.20
Consumptive Use	41.99	31.39	23.74	29.30	32.08	57.15	56.68	12.71	26.00	311.04
Storage Change	9.60	4.00	-25.60	24.45	-28.05	34.15	-4.65	-22.50	-18.20	9.60
Deep Percolation	20.21	0.97	4.46	17.25	5.81	33.44	33.50	9.79	31.13	156.56
Irrigation Efficiencies										
Farm Efficiency	36.6%	77.8%	--	48.8%	21.5%	43.4%	33.9%	--	33.2%	38.4%
Application Efficiency	71.9%	97.3%	--	89.8%	41.0%	73.2%	60.8%	--	59.5%	67.2%
Salt Pickup (tons)	14.1	0.7	3.3	10.4	3.9	17.4	19.9	7.2	18.2	95.1
(tons/acre)	0.94	.05	0.22	0.69	0.26	1.16	1.33	0.48	1.21	6.34

Table 11. 1973 Bulla farm water budget. (10.7 acres of barley)

Budget Item	BUDGET INTERVAL (All values in units of acre-inches) 4/23 to 4/30	5/1 to 5/30	5/30 to 6/7	6/7 to 6/13	6/13 to 6/19	6/19 to 6/24	6/24 to 6/30	6/30 to 7/7	7/7 to 7/10	7/10 to 7/17	Total
Farm Inflows											
Field Tailwater	33.76	0	12.60	0	45.12	0	18.00	51.12	0	28.32	188.92
Root Zone Additions	77.76	0	29.28	0	28.44	0	34.92	61.92	0	32.16	264.48
Precipitation (effective)	12.84	12.52	6.96	0	0.54	0	0	0	0	2.57	35.43
Root Zone Water Budget											
Total Additions	90.60	12.52	36.24	0	28.98	0	34.92	61.92	0	34.73	299.91
Consumptive Use	2.93	32.44	16.13	20.31	13.79	18.32	17.98	28.03	11.56	21.62	183.29
Storage Change	30.92	-40.83	20.00	-26.15	10.49	-19.80	10.06	-8.99	12.00	10.38	-25.92
Deep Percolation	56.75	20.91	0.11	5.84	4.52	1.48	6.88	42.88	0.44	2.73	142.54
Irrigation Efficiencies											
Farm Efficiency	16.9%	--	59.7%	--	32.3%	--	53.0%	16.8%	--	46.7%	24.9%
Application Efficiency	23.2%	--	80.5%	--	82.5%	--	80.3%	30.7%	--	84.7%	40.7%
Salt Pickup (tons)	40.0	15.4	0	4.3	2.7	1.1	4.3	30.2	0.3	1.3	99.6
(tons/acre)	3.74	1.44	0	0.40	0.25	0.10	0.40	2.83	.03	0.12	9.31

study, and the 1971 data presented by Skogerboe and Walker (1972), efficiency determinations have been made for three of the most common crops in the valley; namely, barley, corn, and sugar beets. These data relating to application efficiencies were plotted against time to determine the seasonal variations and the effect of the crop being grown.

In Fig. 19, the seasonal distribution of application efficiency for corn in the test area is plotted. The selected data points represent the three years of data collected on the two farms from which a smooth curve has been sketched in to illustrate the general nature of the seasonal application efficiencies. Although it is apparent that efficiencies increase significantly as the season progresses, a great deal of variation is encountered as a result of year to year changes in soil conditions, irrigation practices, and crop rotations. In addition, some variation may be hopefully attributed to the improvements in water management practices being implemented by the irrigators as a result of the salinity control efforts in the valley.

An interesting comparison which comes from being able to define such curves as Fig. 19 for other crops is the effect on salinity due simply to the variety of crop grown. Efficiency data for sugar beets and barley were plotted against time for several irrigation tests in Figs. 20 and 21. On the Bulla farm during 1972 and 1973 all three crops were grown. From Table 9, the Bulla farm contributed 235.7 tons of salt as a result of growing sugar beets, or 9.2 tons per acre, while the corn and barley cropping contributed 9.3 tons per acre and 6.3 toms per acre, respectively, as indicated in Tables 10 and 11. It is also interesting to note that the 1972 irrigation season produced 21% (41 tons) more salt than the combined total for the 1973 year. Although these figures are few, it is apparent that crop selection may have a pronounced effect on salt loading and additional investigation in this area may be indicated.

The average application or farm efficiency value presented in the "total" column is misleading and often incorrectly used in salinity control discussions. As an illustration, the first two irrigations on the Martin farm during 1972 (Table 7) both had application efficiencies of about 44%, yet the first irrigation caused almost three times as much salt pickup. Thus, an important point to be drawn from Tables 7, 8, 9, 10, and 11 is that the impact of individual irrigations may be drastically different but be of comparable efficiency. Likewise, the obvious importance of the early season irrigation in formulating salinity control strategies is not illustrated. A possible method of adjusting efficiency values by weighting them by the

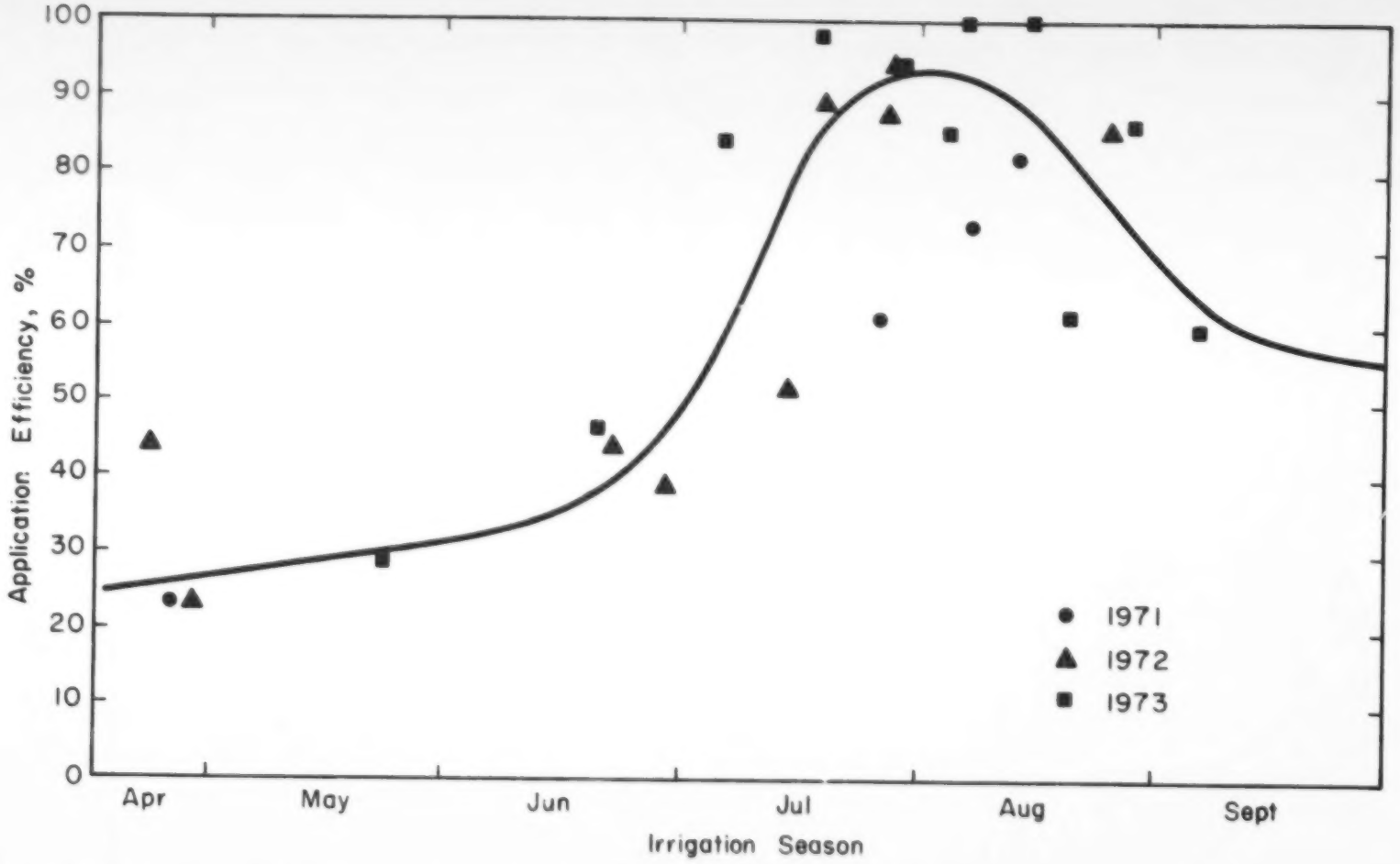

Fig. 19. Seasonal variations in application efficiencies for corn grown in the test area.

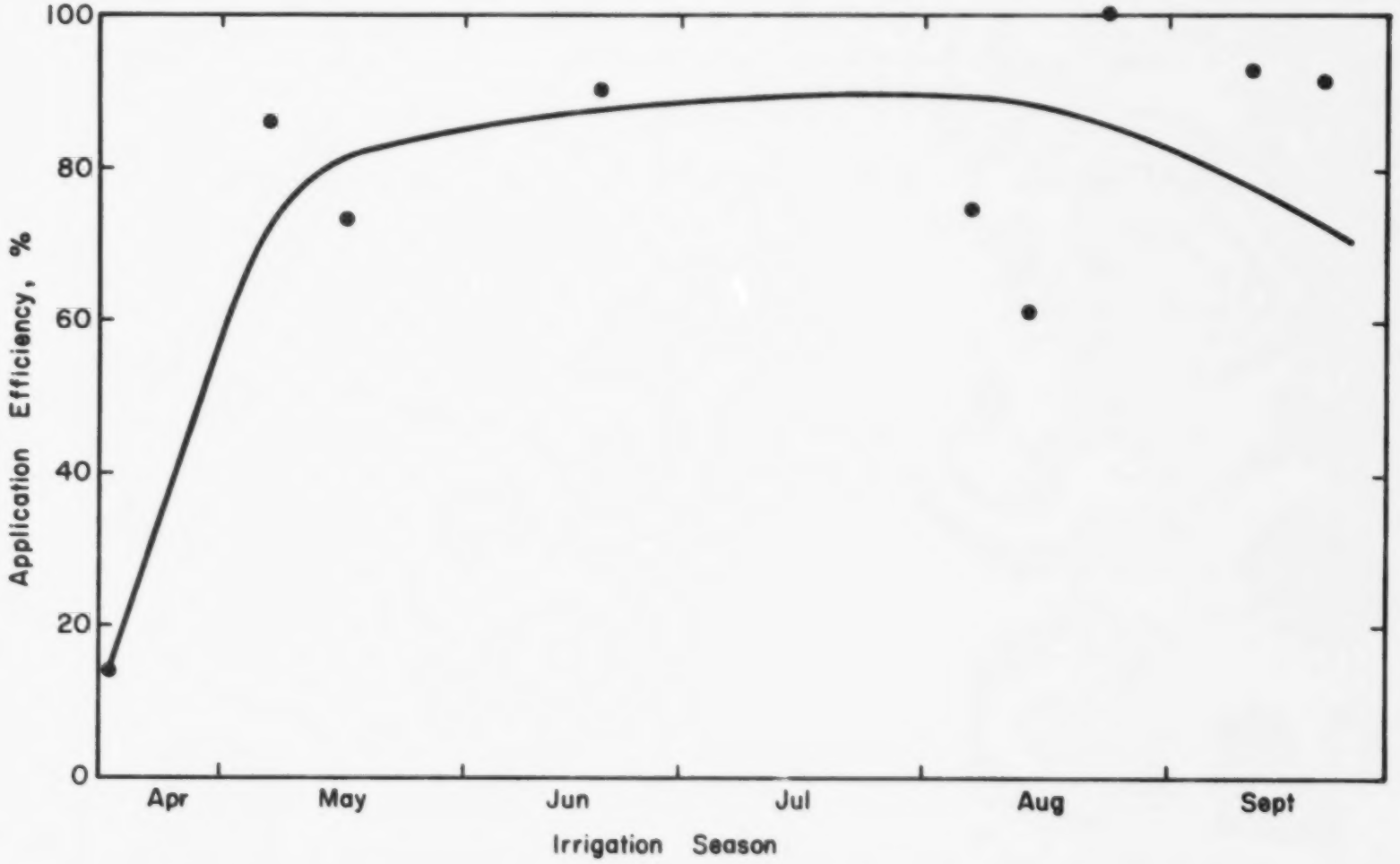

Fig. 20. Seasonal variation in application efficiencies for sugar beets grown in the test area.

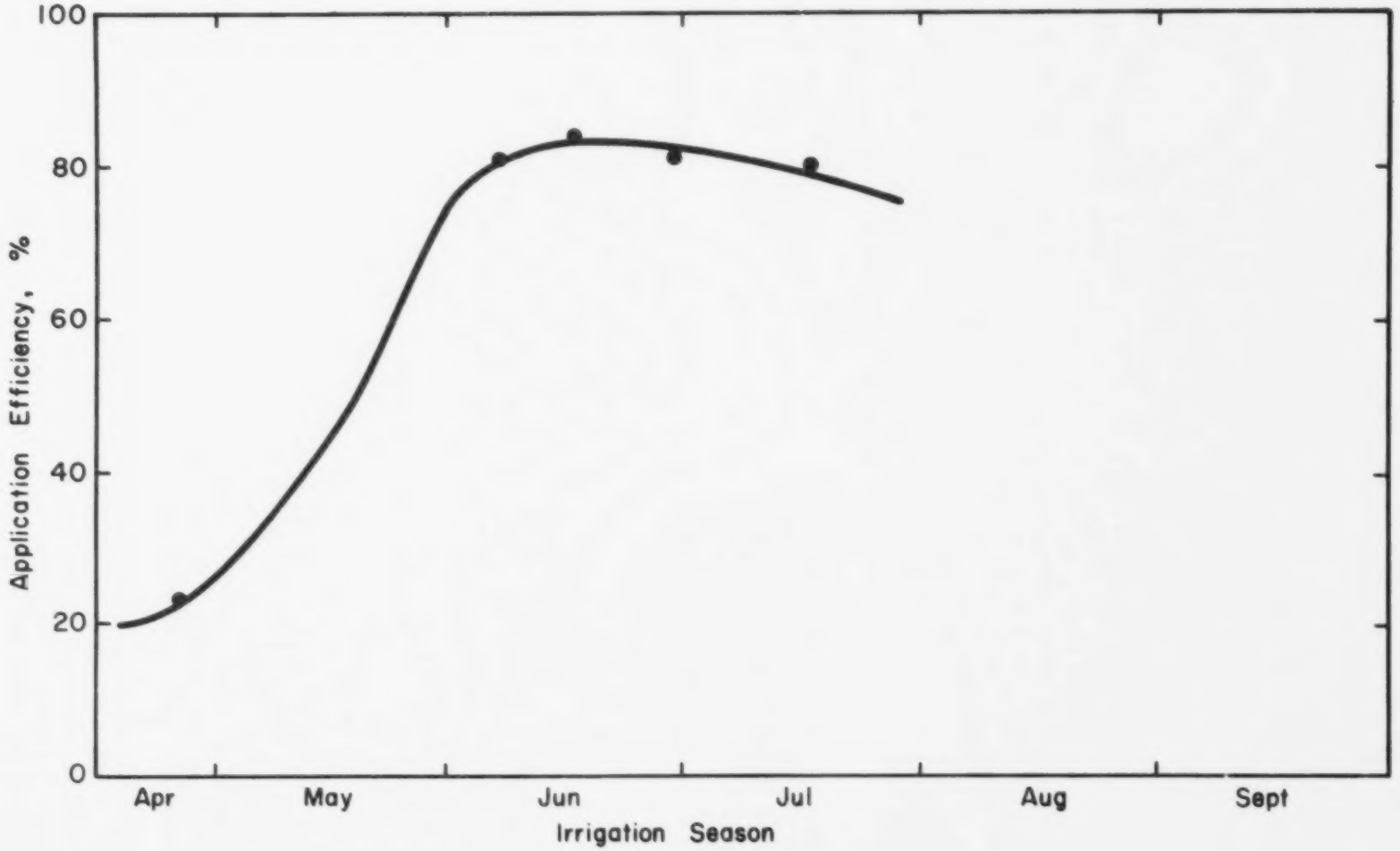

Fig. 21. Seasonal variation in application efficiencies for barley grown in the test area.

magnitude of salt pickup may improve the interpretation of irrigation efficiencies as they apply to salinity.

The results of the budget data in Tables 7-11 show that the goal for salinity control on the irrigated lands of the Grand Valley should concentrate heavily on improving the first two or three irrigations. A further demonstration of this conclusion is shown in Fig. 22 where cumulative applications are compared to cumulative potential evapotranspiration for the sugar beets grown on the Bulla farm in 1972. During April and May, approximately 50% of the water supplied to the root zone is added at a time when less than 20% of the demand is experienced. The comparison in Fig. 22 does not, of course, account for soil moisture storage changes occurring in the root zone, which would change the curves only slightly. In examining the effects of these conditions, it can be seen that salt pickup is also accelerated during this period. For example, the data in the budget tables was plotted in a similar manner in Fig. 23 to illustrate the seasonal variation in deep percolation losses. These results clearly indicate the effects of early irrigations in the Grand Valley, where about 60 percent of the deep percolation occurs in the first two months of the season.

The effects of only the simplest adjustments in irrigation practices during the early segment of the season could produce significant reductions in the salt loadings to the Colorado River. If the quantities of water added to the root zone during each irrigation in Tables 7-11 are divided by the duration of each irrigation, an estimate of the average intake rate can be determined as shown in Fig. 24 for the two study farms. During the first irrigation on the Martin farm in 1972, 80.5 acre-inches were added to the root zone soil moisture storage as a pre-irrigation by applying the water in 24-hour sets. In recalling the shape of the accumulative intake relations shown previously in Fig. 17, the intake after 12 hours would have been about 60% of the 24-hour values for early irrigations. Consequently, a 12-hour rather than the 24-hour set would have cut the application about 40%. Examining data on the other budget variables in Table 7 reveals that deep percolation losses would have been reduced to about 40% (or 18.09 acre-inches of deep percolation rather than 45.05 acre-inches), thus illustrating the scope of the salinity control policy involved in on-farm water management.

The implementation of irrigation scheduling in conjunction with improved irrigation practices on the two farms can also be demonstrated from the efficiency data presented in the budget tables. Application and farm efficiency data for three years on the Martin farm are compared monthly in

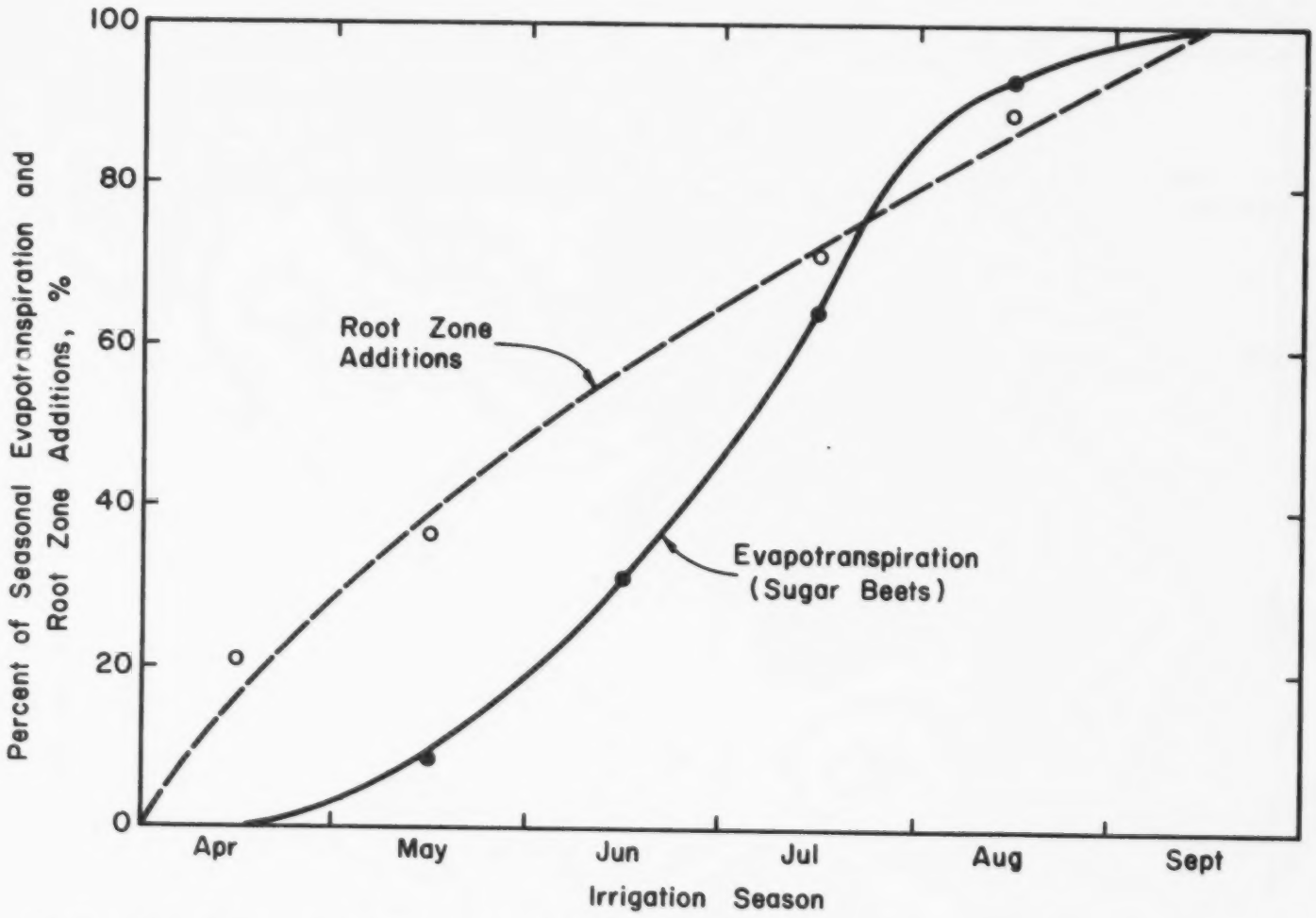

Fig. 22. Comparison of root zone water supply and evapotranspiration demands for sugar beets in the test area.

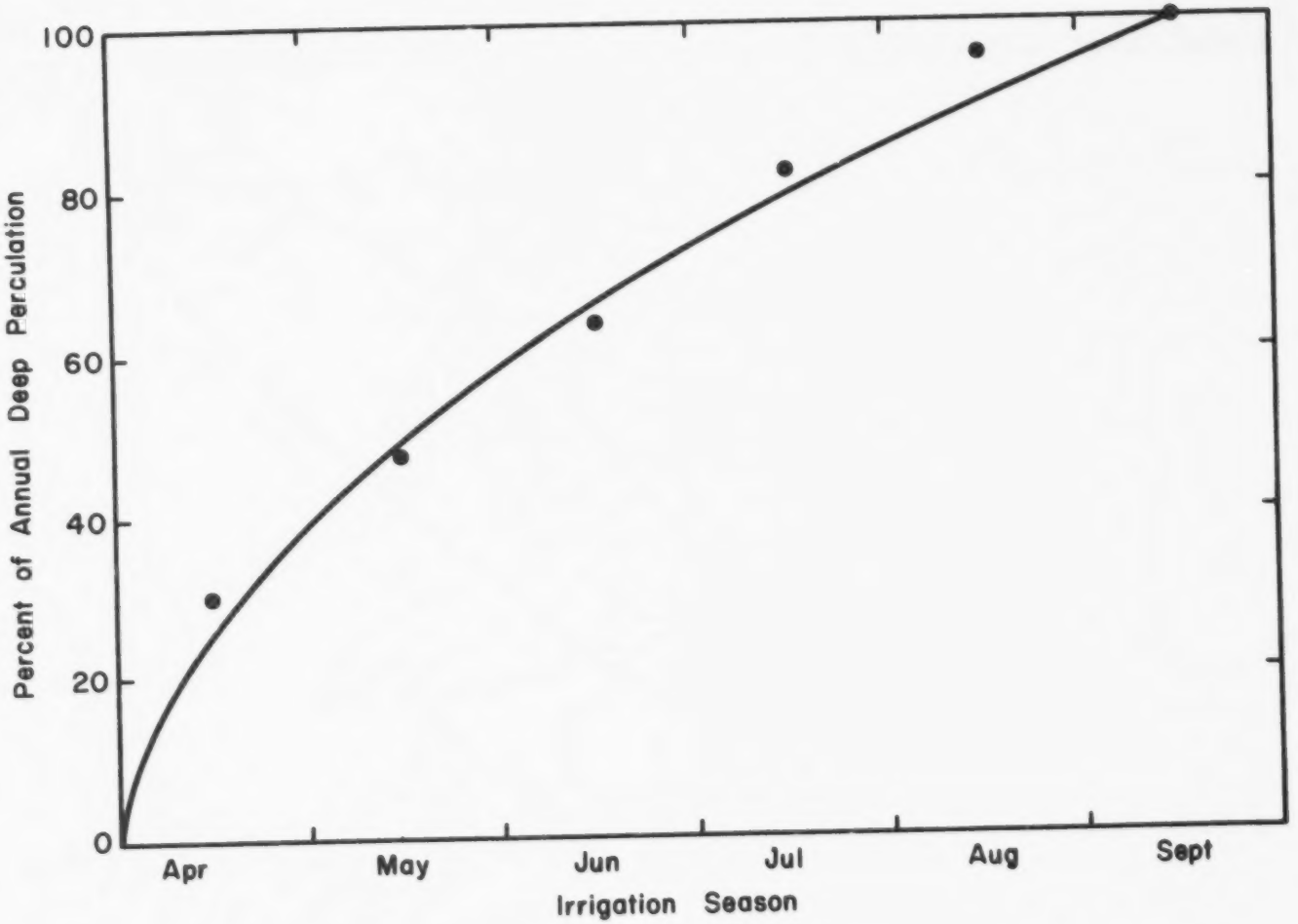

Fig. 23. Seasonal percentage of deep percolation attributed to various irrigations on the farms studied.

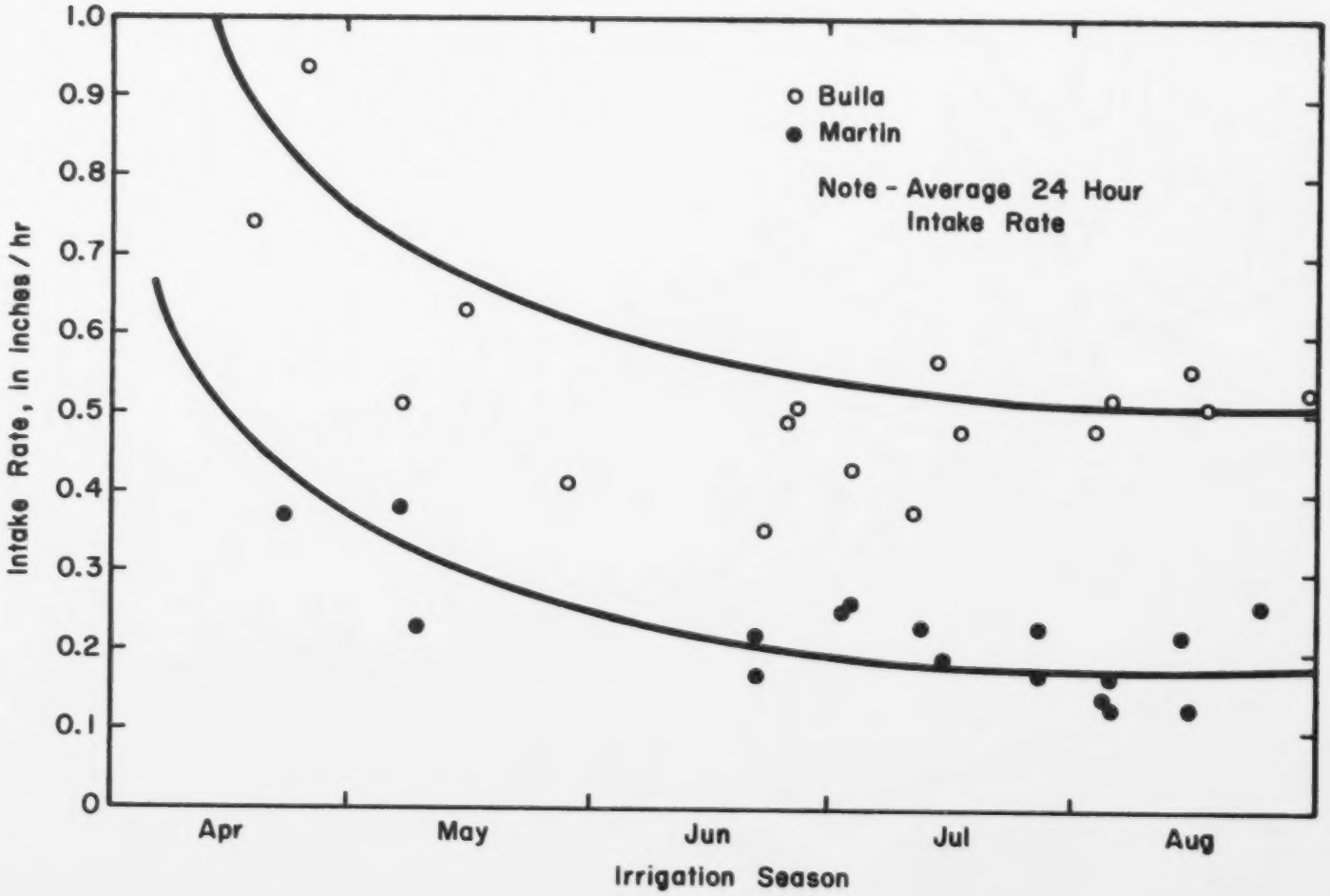

Fig. 24. Seasonal variation in average field intake rates for the Martin and Bulla farms.

Figs. 25 and 26. Except for the May irrigations, a noticeable improvement is demonstrated in these graphs because irrigations were conducted by project personnel. Careful attention given to actual field conditions resulted in considerable success. In fact, a comparison of 1971 and 1973 data indicates a general improvement in application efficiency resulting in significant reductions in salt pickup. However, insufficient care was taken during the initial irrigations due to inexperience, which resulted in large salt loadings.

Data from the Bulla field, shown in Figs. 27 and 28, do not show significant improvement. Although these data represent practices under different cropping patterns, the improvement due to irrigation scheduling remains in doubt. In talking with the farmer, it appears that the irrigation scheduling is having only a marginal effect on his water use practices.

Analysis of Salt Pickup

The last line in each of the budget tables represents the total quantities of salts picked up by the water percolating below the root zone. These values are determined by comparing the total quantities of salts added to the root zone on each individual farm with the flows (water and salt) leaving the study area. Typical salinity concentrations employed in this determination were taken from inflow data and data presented in Table 5.

The data from the two years of this study on each farm were aggregated in a manner shown in Fig. 23 to indicate the seasonal salt contribution from the farms. This analysis, presented in Fig. 29, indicates that almost 60 percent of the salt loading occurs in the April through May period. Skogerboe and Walker(1972) have stated previously that an increase in irrigation efficiency may not be accompanied by an equal percentage reduction in salt pickup. These results substantiate that this conclusion was correct. For example, if the average irrigation efficiency is increased during the April through May period, it is obvious that a great deal more salinity damages can be avoided than a similar increase later in the season when efficiencies are already high and would be difficult to improve.

Over the years of study in the Grand Valley, several researchers have determined the total pickup from the area in terms of contribution per acre. The U. S. Environmental Protection Agency (1971) stated this value to be about 8 tons

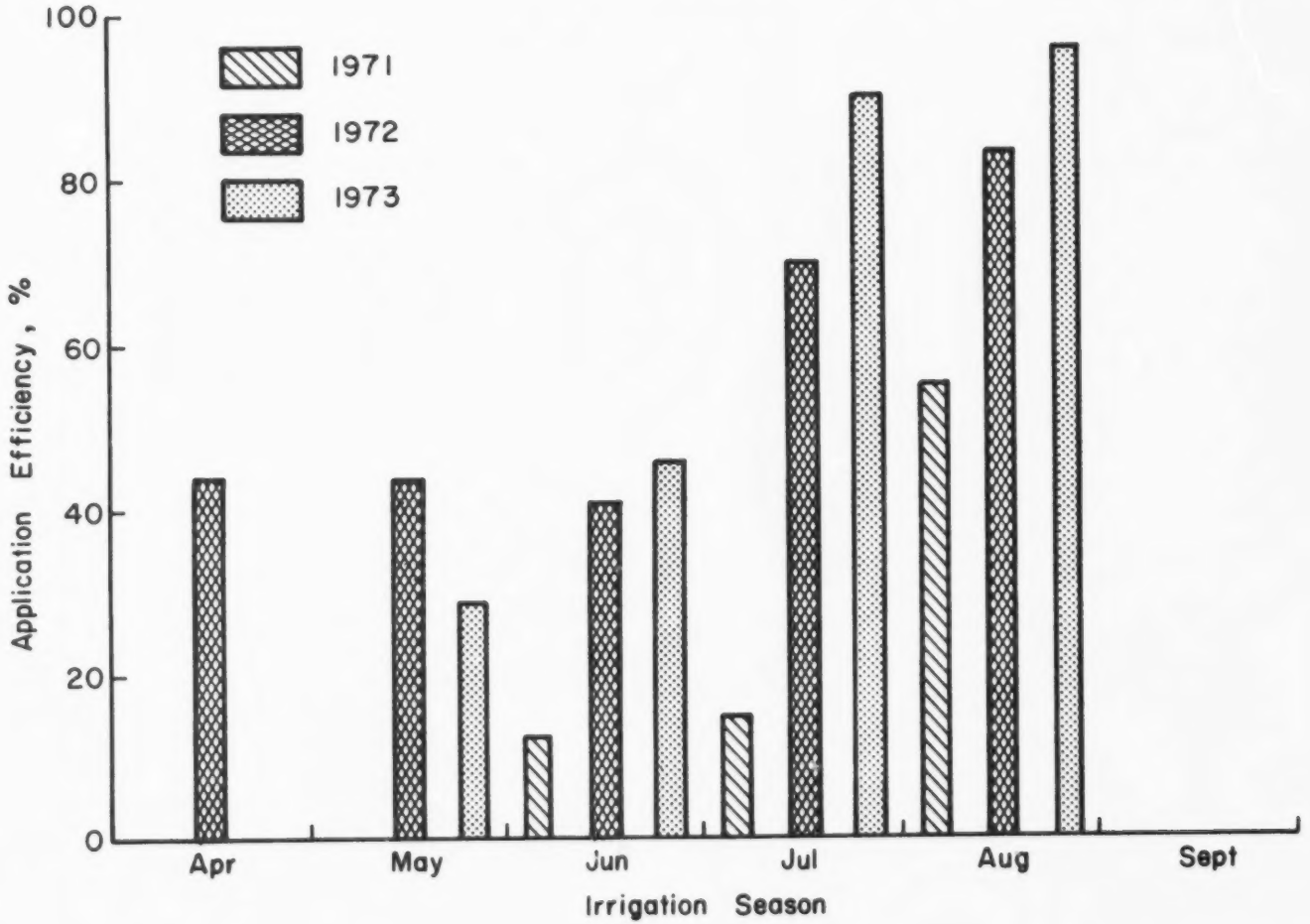

Fig. 25. Comparison of application efficiencies for the Martin farm before and after the implementation of irrigation scheduling.

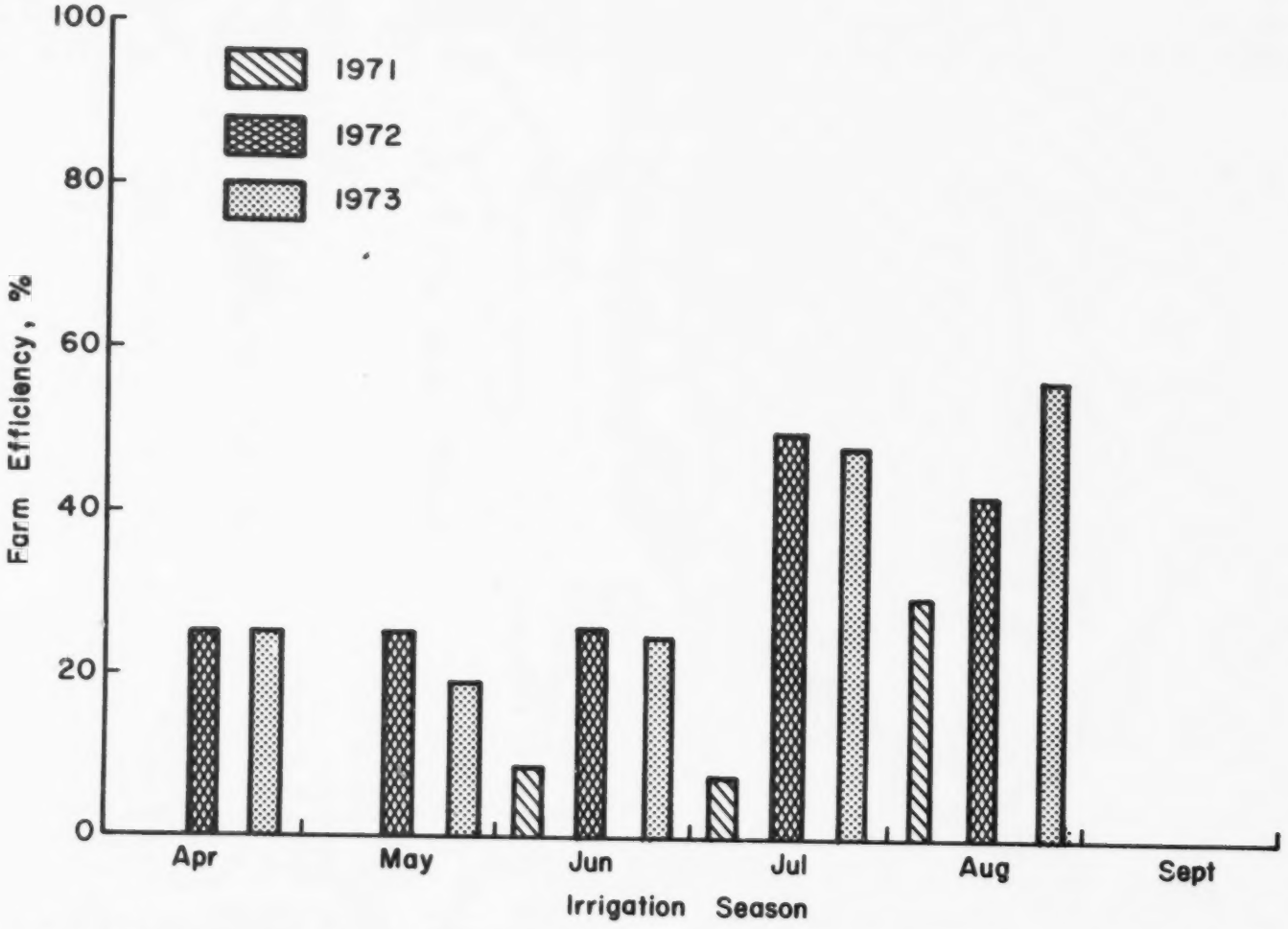

Fig. 26. Comparison of farm efficiencies for the Martin farm before and after the implementation of irrigation scheduling.

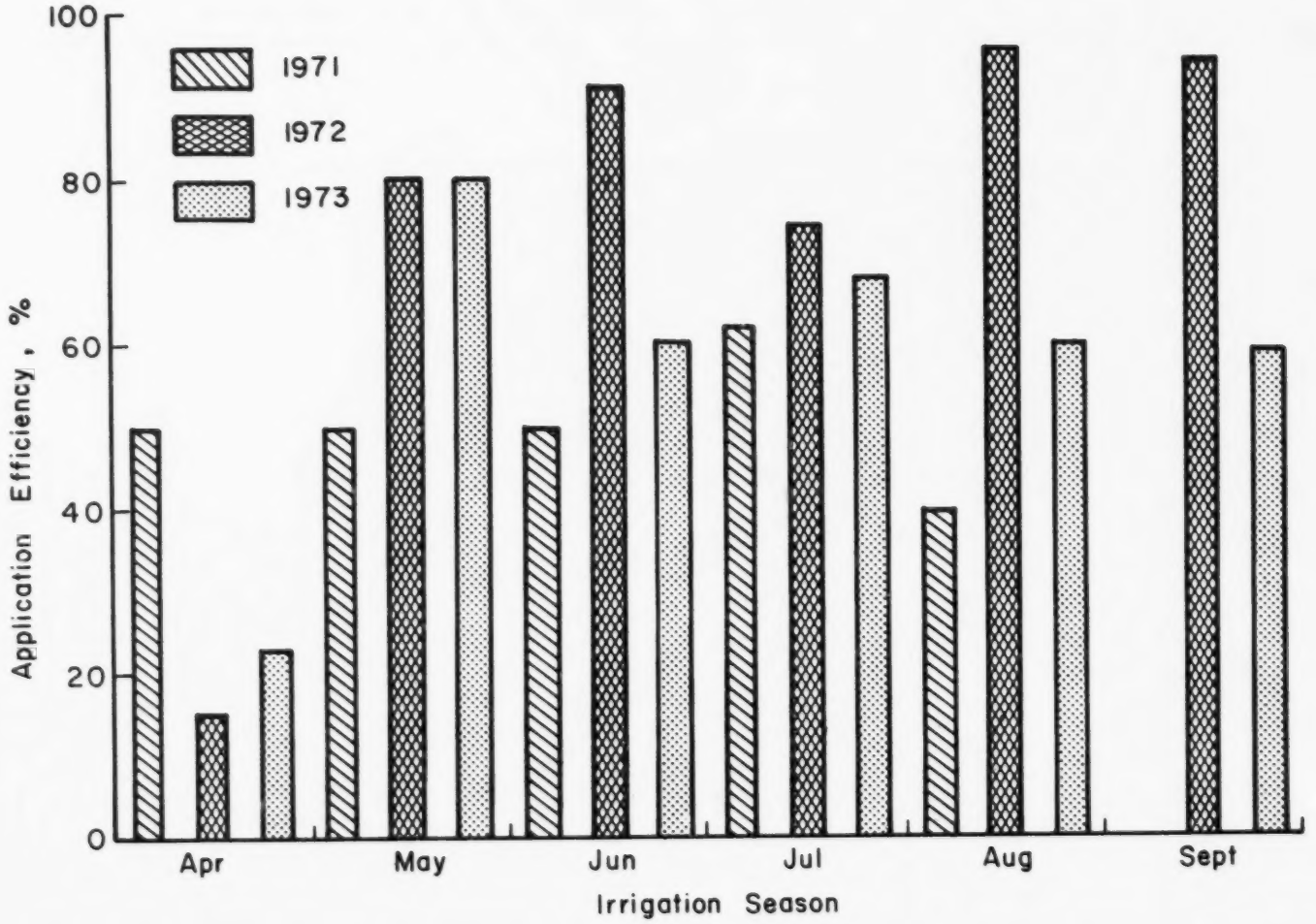

Fig. 27. Comparison of application efficiencies for the Bulla farm before and after the implementation of irrigation scheduling.

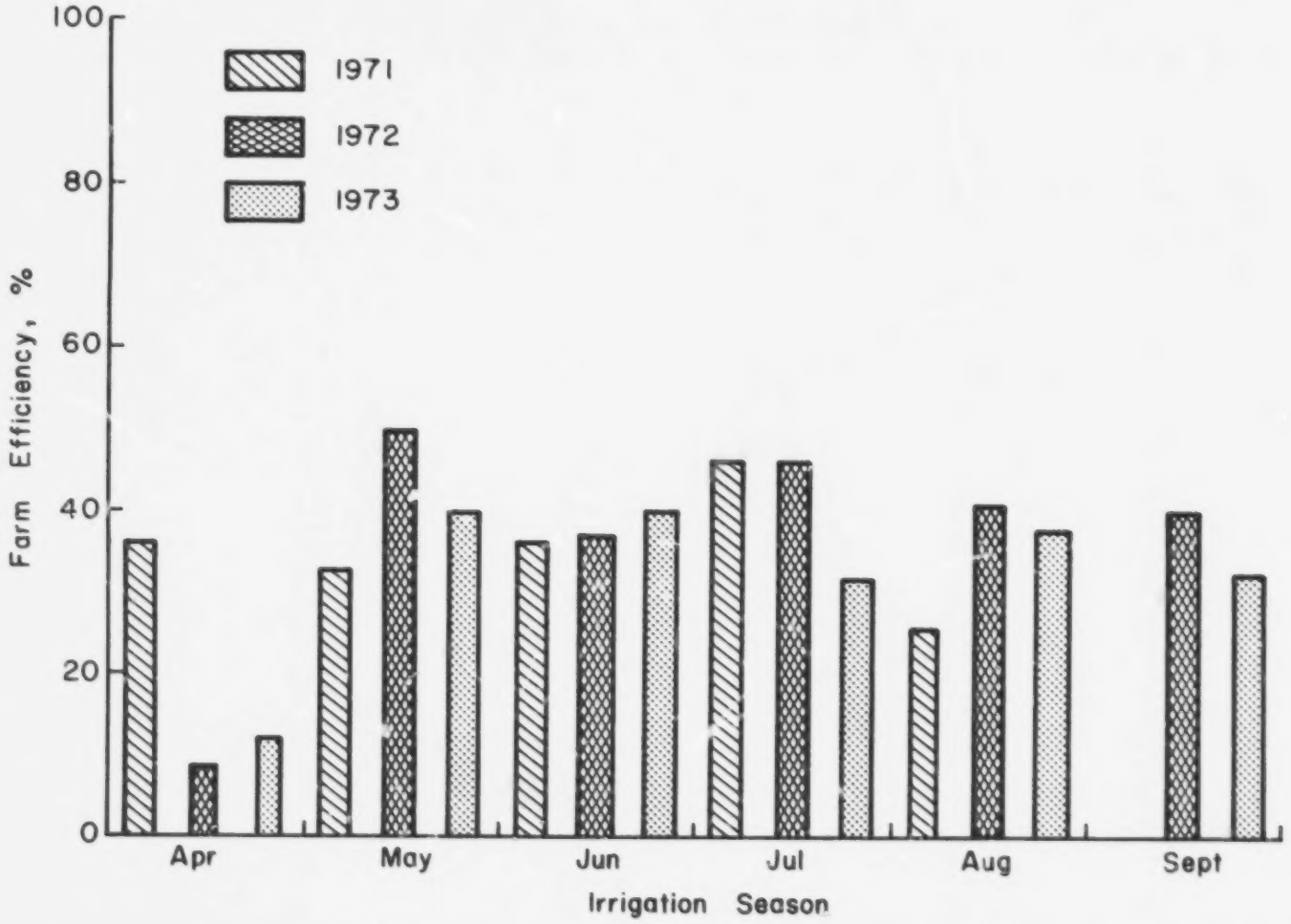

Fig. 28. Comparison of farm efficiencies for the Bulla farm before and after the implementation of irrigation scheduling.

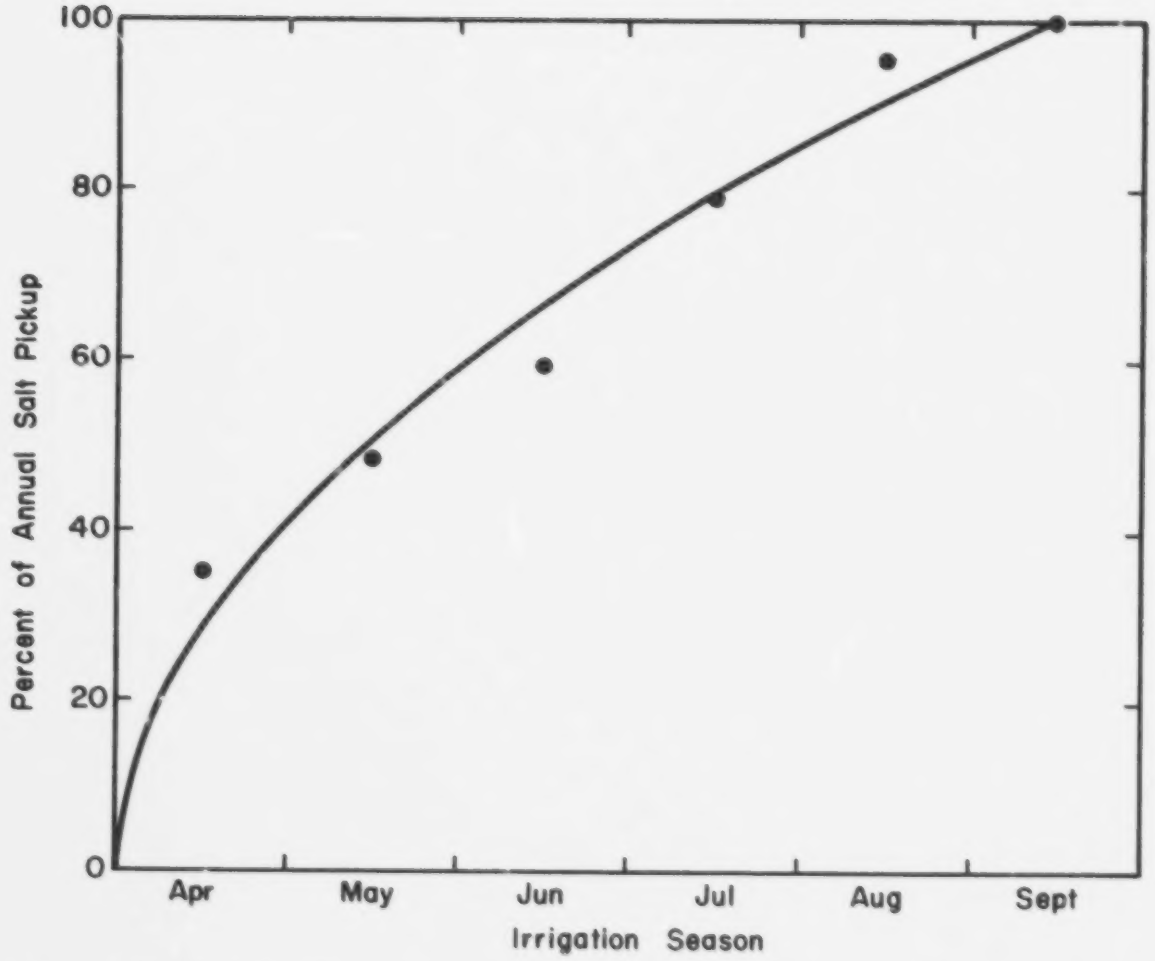

Fig. 29. Seasonal distribution of salt pickup from the farms in the test area.

per acre, while Skogerboe and Walker (1972) listed a value of approximately 12 tons per acre. The difference between these two values is found in the number of irrigated acres involved in the computations. Until 1971 when Walker and Skogerboe (1971) completely mapped the valley, typical estimates of irrigated acreage were about 120,000 acres, while the actual values were slightly over 70,000 acres. On the basis of these facts, the existing estimates of salinity contribution per acre are reconciled. In the data presented in Tables 7-11, and using values for groundwater quality listed in Table 5, the salt contribution per acre on the Bulla and Martin farms ranged between 8.1 and 9.2 tons per acre. However, other groundwater data taken from drains and wells indicate the values in Table 5 are at the lower limits of the variation encountered. Data from the upper limit wells show that the per acre contribution ranges between 10.6 and 12.6 tons. Consequently, the values were established again by this study as being in the range of 9-12 tons per acre. Since this study is based on more exhaustive data, than were the conclusions of earlier studies, the reliability of these results are substantially reinforced.

IRRIGATION SCHEDULING IN GRAND VALLEY

The results discussed in the previous paragraphs demonstrate that the potential effects of irrigation scheduling could be most significant if both the timing and quantity of irrigation applications can be controlled. In the Grand Valley, as well as most irrigated regions, the effectiveness of irrigation scheduling as a salinity control measure is contingent upon the degree of service provided to the farmer. An additional important factor is the irrigator's ability to achieve the suggestions provided by scheduling services. This study has focused the attention of the investigators on topics that are influential towards the successful use of irrigation scheduling in Grand Valley: (1) flow measurement; (2) water control; (3) communication of data; and (4) local administration.

Water Measurement

Even though the quantity of water required by the root zone conditions may be listed in the irrigation scheduling computer printout, the reality of the Grand Valley situation is that irrigators do not know how much water is entering the root zone. Only a very few farms have a flow measuring device at the farm inlet. The only farms where measurements are actually recorded are those involved in research studies.

Consequently, the utilization of irrigation scheduling in Grand Valley is unlikely to produce any substantial reductions in the valley salt loadings, because there will be no reductions in water passing through the root zone unless measuring devices are employed and the amount of water applied is controlled. The results presented earlier reinforce this conclusion.

The practices which have yielded these conditions are primarily twofold. First, the irrigation companies relinquish their responsibility for the water immediately upon diversion from the canal turnout gate into the lateral subsystem. Some lateral diversions have as many as ten or twenty individual irrigators subscribing to the flow. Since an understandable inequity exists in the allocation of the water among the several interests, a tendency exists to supply enough water to meet each demand. Previous studies by project personnel have shown that most turnout gates discharge significantly more flow than is listed as the water right. In fact, Skogerboe and Walker (1972) report that the water duty for the valley often ranges between seven and ten acre-feet per acre of irrigated land annually. The second dimension relative to local water management is related to the first in that the cost of water is so low as to render economic incentives for more efficient use nonexistent.

The first requirement to overcome laxity in water management is standardized flow measurement. If ditch companies insist on controlling only canal or ditch flows, then they should deliver only the prescribed flow to each lateral. Legal history and experiences are replete with examples indicating that diverting water in excess of the required supply does not insure the validity of the right. In examining historical land use changes, the irrigable acreage has been markedly decreased by roads, ditches, homes, schools, etc. Consequently, flow measurement at the canal turnout is needed to reduce wasteful and salt-loading water use practices. Water measurement is also needed between the canal turnout and the field head ditches to indicate to the farmer how much water he is applying.

Water Control

The judicious use of water on agricultural lands requires careful consideration of the factors which affect the irrigator's ability to control and regulate his water supply. Some of the more important of these factors are structural items like check structures, division boxes, and drops, as well as nonstructural factors such as farmer attitudes, irrigation practices, and system flexibility.

The condition of the water delivery network which operates between the canal turnout and the field head ditch is generally in a state of disrepair for most areas in the Grand Valley. Laterals that are not eroding deeply into the soils are heavily infested and obstructed with weeds and debris. At locations where water is divided among two or more irrigators, the typical wood or concrete checks and dividers are in need of both rehabilitation and redesign.

The farmer is the first link in the food and fiber production chain and he takes numerous risks, requiring conservative judgment in most decisions. Subsequently, innovations to the agricultural industry must be adequately demonstrated before wide acceptance is achieved. Under the objectives of salinity control, the incentives which would encourage an irrigator to participate in an irrigation scheduling program also include convenience, increased productivity, as well as decreasing downstream damages. As a result, improved control of water resources should be presented as an approach to minimizing the detrimental effects of inefficiency in crop production.

Farming practices have a pronounced effect on water use. For example, in the Grand Valley the tendency is to irrigate the crops the same way during each irrigation. In the early part of the growing season, when plant water needs are low and the topsoil is kept moist to facilitate good plant emergence, excessive water is applied resulting in high deep percolation losses.

Different irrigation practices have different labor, capital, and time requirements. The labor required for a sprinkler system would, for example, be generally less than the flood types and thus facilitate water use improvements by the irrigator, but at an increase in capital investment. During the 1973 irrigation season, the labor requirements for making an irrigation set on a furrow system using plastic dams to raise the water surface and siphon tubes to get the water to the furrows were determined as a means of evaluating the labor necessary to improve irrigation efficiencies. The study was conducted in the head ditch of the Martin farm using plastic dams to control water levels in the ditch. With the water supply available, it was possible to run on the average 47 of the one-inch diameter siphon tubes or 25 of the 1-1/4-inch tubes. The 1-inch size was used mostly to provide better control of the water (field tailwater was reduced), as well as using more tubes simultaneously in order to reduce the total time to irrigate the field. A set was changed by pulling the dam and moving it 47 furrows across the field and then re-installing and sealing the portable dam. All the tubes must be picked up, moved and

restarted. In this study, it was found that one inexperienced man could set 47 tubes in less than twenty minutes, or at a rate of about 2.5 tubes per minute. In a previous paragraph, the effect of reducing the time water is applied to the Martin farm was shown to have a substantial impact on decreasing deep percolation losses. Recalling that during the first irrigation in 1972, deep percolation losses could have potentially been reduced from 45.05 acre-inches to 18.09 acre-inches by irrigating in 12-hour sets rather than the usual 24-hour sets. This improvement, which would decrease salt loading by an estimated 27 tons, could have been accomplished with only one hour more labor being invested.

One of the important nonstructural improvements which could be undertaken involves the flexibility of the system to adjust irrigation and cropping practices to meet the seasonal changes which occur in water supply, soil conditions, climatological events, and economic demands. Farming practices are particularly affected by changes in these factors. During some years, the land may not have been properly prepared due to late precipitation or difficulty in scheduling the use of farm equipment. The water requirements, length of irrigations, and cropping rotations may then require alteration to maximize economic return while minimizing salt pickup. Occasionally, periods of water or nutrient shortages, as well as energy shortages, may necessitate changes in farming practices. A great deal of adjustment in this area is needed, not only by the farmer, but also by those who serve his material and service needs—and good water control is especially important in meeting necessary adjustments.

Communication of Data

Probably the most critical need for the irrigation scheduling program itself is an effective line of communication between the irrigator and the computer. It is apparent in the Grand Valley, judging from recent experiences, that such lines have not become properly functional. A farmer may be reluctant to accept scheduling when the schedule repeatedly calls for an irrigation while his crop of alfalfa has just been cut and is still on the ground. Apparently, one farmer in Grand Valley withdrew from the program because of this very problem. Yet, the program really has no means of knowing the crop has been cut if the information that was provided says only that the root zone has been depleted past its limit and an irrigation is needed. In this case, the field representative has failed to determine the field conditions, and the farmer has not voluntarily supplied the necessary information.

Since the scheduling depends to a large extent on the soil moisture in the root zone, some decision must be made as to where the samples should be taken in the field. This location can determine the time between irrigations because the time depends on the available moisture in the root zone. By looking at Fig. 30, which was taken from data collected on the Martin farm during 1972, the moisture variation across the furrow at various depths can be seen. By taking the samples at different locations, different moisture contents will be obtained which in turn would offset the computed water depletions, thereby resulting in different dates to begin irrigation. If the moisture sample was taken in the furrow rather than in the crop row, there may be some additional time between irrigations which would correct the problem of poor irrigation timing being experienced on some fields. It may be advisable to sample soil moisture at various locations in order to select one which is representative of the typical field conditions.

Local Administration

It has previously been noted that existing concerns for salinity control and local farming attitudes have not been congruent. This can also be generalized for the local institutions which may be available to promote more efficient use of water. One of these is the linkage between irrigator and canal company in which responsibilities do not overlap, which hinders water control along the laterals. Another is the possibility associated with consolidating various levels of water management to achieve a system which is more responsive to the political realities of salinity in the Colorado River Basin. In addition, the solicitation of funding to effect salinity related improvements by local groups deserves further attention. In these areas and others, additional study should be given to their opportune use.

EFFECTIVE SCIENTIFIC IRRIGATION SCHEDULING

A schematic representation of an effective irrigation scheduling program is shown in Fig. 31. Irrigation scheduling consists of two primary components; namely, evapotranspiration and available root zone soil moisture. The climatic station portrayed in Fig. 31 represents some of the climatic data that must be collected in any irrigated area in order to calculate daily evapotranspiration.

The other major category of required data pertains to soil characteristics. First of all, field capacity and wilting point for the particular soils in any field must be determined. However, the most critical data are the infiltration (intake) characteristics of the soil. Although there are many techniques for measuring infiltration, the data for

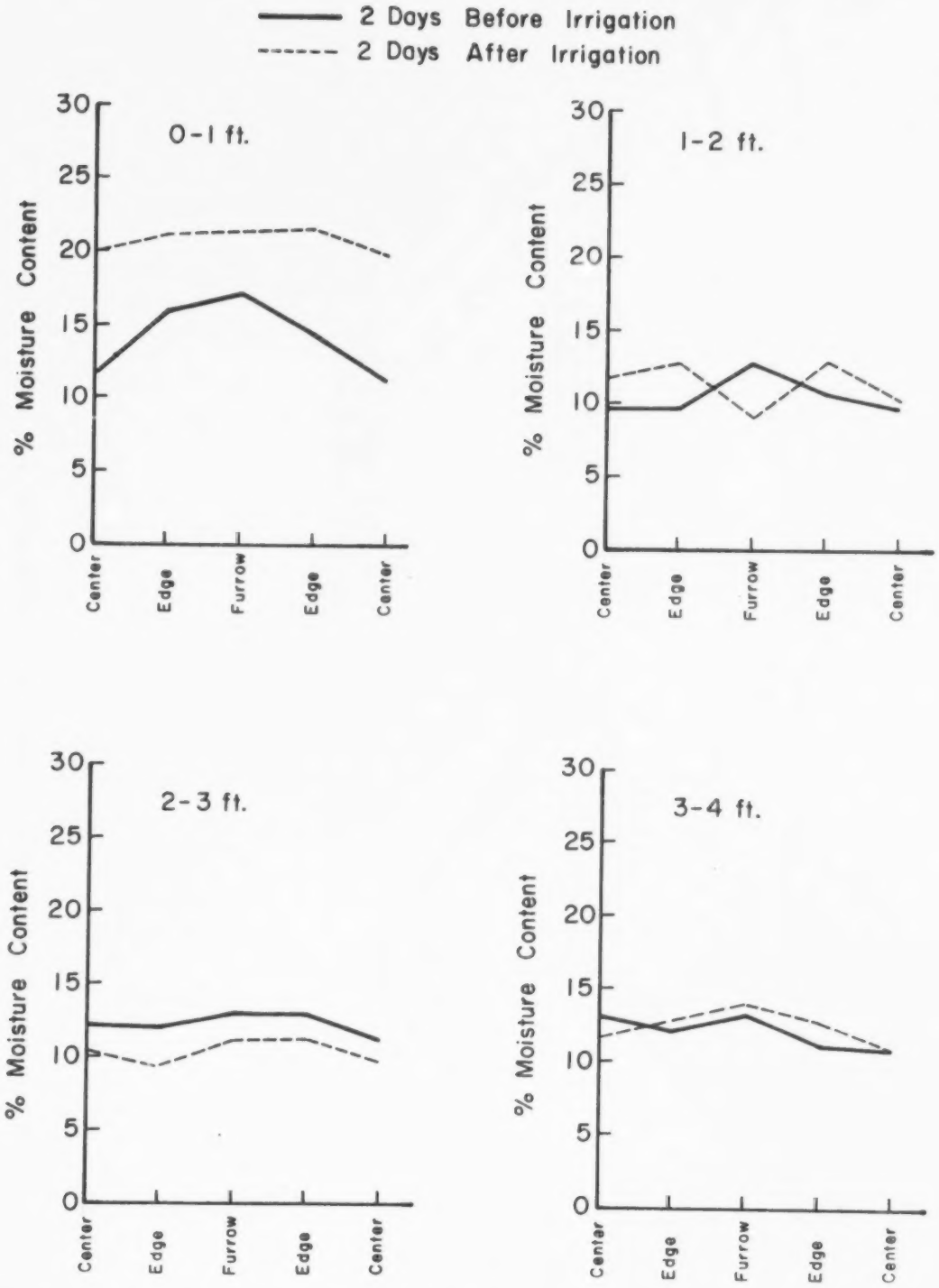

Fig. 30. Soil moisture variations in the crop root zone.

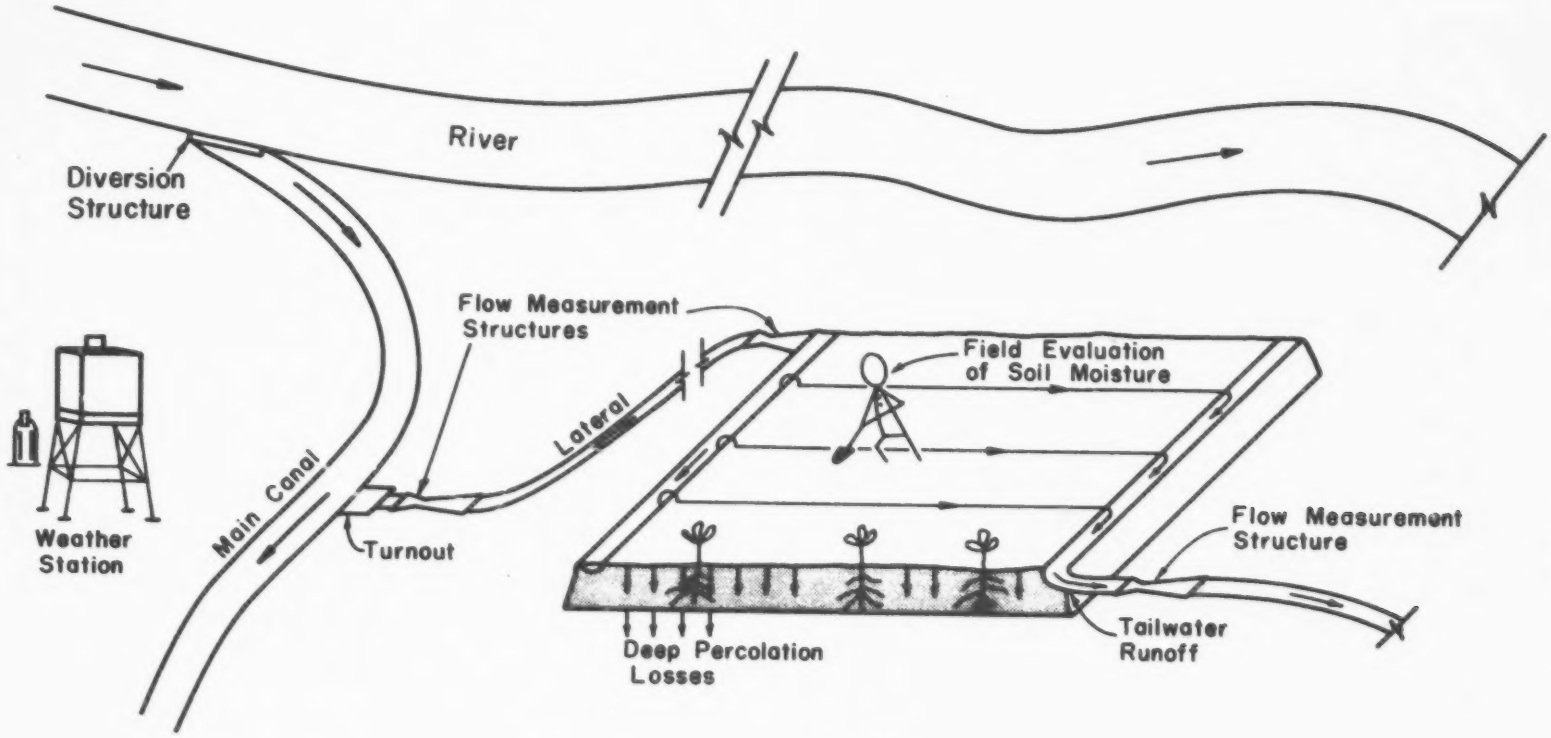

Fig. 31. Schematic of requirements for effective irrigation scheduling.

furrow irrigation can be obtained from advance-recession tests and infiltrometer rings. Only by knowing how intake rates change with time during a single irrigation, as well as throughout the irrigation season, can meaningful predictions be made as to: (a) the quantity of water that should be delivered at the farm inlet for each irrigation; and (b) the effect of modifying or changing irrigation practices upon deep percolation losses.

With good climatic data and meaningful soils data, accurate predictions as to the next irrigation date and the quantity of irrigation water to be applied can be made. In order to insure that the proper quantity of water is applied, a flow measurement structure is absolutely required at the farm inlet.

SECTION VII

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SECTION IX

LIST OF SYMBOLS

Symbol	Definition
a, b, a_1, b_1	regression coefficients
E_f	farm efficiency, %
$\overline{E}_t$	expected evapotranspiration, inches
E_{ta}	potential evapotranspiration of well-watered alfalfa, cal cm^{-2} day^{-1}
E_{tg}	potential evapotranspiration of well-watered grass, cal cm^{-2} day^{-1}
e	vapor pressure, mb
G	sensible heat flux, cal cm^{-2} day^{-1}
M_o	maximum allowable soil moisture depletion, %
M_d	existing soil moisture depletion, %
N	time until next irrigation in days
R_b	net outgoing thermal radiation, cal cm^{-2} day^{-1}
R_n	net radiation, cal cm^{-2} day^{-1}
R_s	solar radiation, cal cm^{-2} day^{-1}
T	average daily temperature °F
T_k	temperature, °K
T_x, C_t	regional constants
u_2	wind speed at a specified height of z, miles per day
W_a	water to be applied, inches
α	albedo
Δ	changes in saturation vapor pressure with temperature, mb/deg
γ	dry air property, mb/deg

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